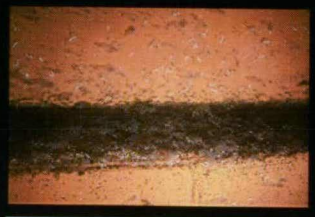
Keeping the coastlines of the Southern Ocean pest-free

Hazards, risks and management of non-indigenous species in high latitude marine environments



Patrick N Lewis

Keeping the Coastlines of the Southern Ocean Pest-free

Hazards, risks and management of non-indigenous species in high latitude marine environments

By

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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

University of Tasmania

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Statement of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due acknowledgement is made in the text.

Patrick N Lewis Date 23-05-07

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Dedication

To Kate
For her patience
And my parents
For their pride

Abstract

Invasive species are a prominent threat to global biodiversity. In the marine environment of the Southern Ocean, the rate of delivery, establishment and the subsequent impacts of non-indigenous species remains poorly understood. Furthermore, the absence of dedicated monitoring and effective baselines makes it difficult to recognize the presence of invasive populations. It is now understood that several introduction pathways capable of delivering marine species operate in this region, and the first introduced marine species in the Antarctic continent was recently reported. By analysing various stages in the transport pathway, this work provides key information to supplement our current understanding of this threat.

In the Southern Ocean, the natural transport mechanism for shallow-water marine organisms provided by kelp rafts is being augmented by plastic debris and shipping activity. Plastic debris provides additional opportunities for dispersal of invasive organisms, but these dispersal routes are passive, dependent on ocean currents, and already established. In contrast, ships create novel pathways, moving across currents and often visiting many locations over short periods of time. Vessel traffic thus poses the most likely mechanism by which exotic species may be introduced to the Southern Ocean. While this hazard incorporates a variety of specific mechanisms such as ballast water, entrained objects and hull fouling, an assessment of these pathways demonstrates that hull-fouling communities are the most likely avenue for marine introductions.

Introductions can also occur at the level of the genotype. Remote populations of *Mytilus galloprovincialis* (blue mussels) from the New Zealand sub-Antarctic islands possess a unique genetic structure and should be considered as a sub-species within the *Mytilus* complex. Such populations represent valuable examples of genetic information in a species with a genetic structure clearly homogenized through human transport opportunities. These unique populations are at risk of hybridization with cosmopolitan gene-lines sourced from temperate ports. The ability of invasive species to gain rapid anthropogenic dispersal also threatens the genetic diversity of the entire species. This loss of genetic diversity is an additional component of biodiversity loss associated with the spread of non-indigenous species.

By identifying high risk species, surveillance and monitoring activities can focus upon species of concern allowing resources to be allocated more efficiently. Temperate fouling communities were collected on settlement plates and exposed to thermal conditions replicating Southern Ocean environments to determine high risk species. A wide variety of temperate species survive the thermal conditions of the sub-Antarctic islands and at least eight species can survive in the waters of Antarctica. Three species (*Halicarcinus innominatus, Petrolisthes elongatus* and *Mytilus galloprovincialis*) are capable of spawning and completing their entire life-history cycle at Southern Ocean temperatures.

The data collected in this thesis have been incorporated into an assessment of the risk of marine introduction to the sub-Antarctic Macquarie Island Marine Park. Analyses of environmental tolerances show that at least seven species of invasive marine pests, resident in ports in Australia and New Zealand, could potentially survive and complete their life cycles in the water temperatures that are found at Macquarie Island. Management recommendations include the instigation of baseline monitoring programs and operational procedures aimed to minimize the ship-based transport of marine species.

Statement of publication and co-authorship

Publications produced as part of this thesis:

Lewis, P.N., Riddle, M.J. & Hewitt, C.L. (2004). Management of exogenous threats to Antarctica and the sub-Antarctic islands: balancing risks from TBT and non-indigenous marine organisms, *Marine Pollution Bulletin.* 49: 999-1005.
Proportion of work: Lewis: 80%. Riddle: 10%. Hewitt: 10%.

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The following people and institutions contributed to the publication of the work undertaken as part of this thesis:

- *Andrew McMinn (University of Tasmania), Martin J. Riddle (Australian Antarctic Division) and Chad L. Hewitt (Australian Maritime College) assisted with guidance and general supervision in all aspects of the PhD study and the production of publishable manuscripts.*
- *Simon Jarman (Australian Antarctic Division) provided supervision, guidance and assistance for the molecular research component.*
- *Rupert Summerson (Bureau of Rural Science) contributed to the risk assessment for Macquarie Island*
- *Steve Smith (University of New England) contributed information and advice in the analysis of kelp as a transport vector in the Southern Ocean*
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We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published (or submitted) peer-reviewed manuscripts contributing to this thesis:

Andrew McMinn	Larry Forbes
(Candidate's Supervisor)	(Head of School)

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Section I

Non-indigenous species and the Southern Ocean: Scope, vectors and management

"There is a possibility... that these creatures may have traveled out from our waters along with the vessel to the southern latitudes at which they were caught"

Stebbing, T.R.R. (1888) in regards to an amphipod collected during the first scientific voyage to the Antarctic Circle aboard *HMS Challenger*.

The expedition of the *HMS Challenger* heralded a new era of discovery in the waters of Antarctica, yet the astute observations of Thomas Stebbing demonstrate that even these first voyages into this "last frontier" probably carried an assemblage of organisms native to the ports that lay in the vessels' wake. The species in question, *Jassa (Podoceros) falcate* (Amphipoda), is indeed likely to have traveled to Heard Island clinging to the wooden hulls of the arriving vessels amidst the diverse fouling communities that typically coated wooden sailing ships of the era. This perceptive acknowledgement that humans may carry non-indigenous marine species into Antarctic waters has been in print for over 100 years; however this period has seen little to expand upon our understanding of the process of human-mediated marine introductions in the Southern Ocean. While a few authors have again commented upon fouling assemblages associated with Southern Ocean vessels (e.g. Chilton, 1910), until very recently virtually no consideration has been given to the potential for such species to be liberated in high latitude environments, or to the potential impacts that their establishment might have upon native ecosystems.

The failure to recognise the potential impacts of non-indigenous species in the marine environment is in stark contrast to the logistical and scientific investment in the management of introduced populations in the terrestrial environment of the Southern Ocean islands. Over 200 non-indigenous organisms[1] have been recorded from these remote environments (Frenot, 2005), and their presence has engendered a range of management programs aiming to exterminate or control these alien populations (e.g. Cooper *et al.*, 1995; Torr, 2002; Towns & Broome, 2003; Copson, 2004; Frenot *et al.*, 2005). Non-indigenous species have also reached the Antarctic continent, with transient insect populations being recognised around research bases (AAD, 2006), and recently the introduced grass, *Poa annua*, has been found to be spreading aggressively in the maritime Antarctic in response to the regional warming (Olech, 2006). These introductions are

[1] Non-indigenous species (NIS) is used in this thesis to designate species that have been introduced to a region outside of their natural range of dispersal and evolution. Where such species have been shown to cause distinct impacts to native ecosystems or human health, such species are termed invasive.

readily recognised due to their proximity to human operations in the area; however below the high tide mark, changes in biological communities are less easily identified.

Despite the absence of any concerted effort to search for introduced populations in the marine environment, the research community has recently been alerted by the inadvertent discovery of an introduced spider crab (*Hyas araneus*) in the waters adjacent to the Antarctic Peninsula (Tavares & De Melo, 2004). In conjunction with a single publication describing the pathways for non-indigenous species into the Southern Ocean (Lewis *et al.*, 2003), the discovery of this marine introduction in Antarctica has raised an urgency to gain an understanding of the process and pattern of activities that facilitate the advention of marine species in these waters. Although the past three years have witnessed several international meetings in which marine introductions have been a central topic of discussion (e.g. Antarctic Treaty Committee for Environmental Protection Meeting VIII, 2005; Non-native species in the Antarctic – a workshop, 2006), the primary realization of such meetings are that at present, the research community does not hold sufficient knowledge to effectively manage our activities in the region to mitigate the risk of introduction.

This dissertation addresses some of the major gaps in our knowledge of marine introductions in these remote waters[2]. The approach has focused upon describing the entire pathway of marine introductions and to examine key points along this chain of events where sound management practices can be instigated to minimise this threat. Thus the thesis is divided into a number of sections that deal with discreet issues that are central to the control of non-indigenous species introduction in high latitude coastlines. These sections deal with:

- Section I: The transport pathways operating within the Southern Ocean region;
- Section II: The potential for introduction of alien genetic material to isolated populations;
- Section III: The ability of temperate species to survive the thermal conditions of Antarctica and the sub-Antarctic islands; and
- Section IV: The application of risk assessment techniques to describe the risk of marine introductions to Macquarie Island and to recommend management practices for this region.

[2] NB: This thesis follows an earlier body of work (Lewis, 2001) submitted for the degree of Bachelor of Antarctic Studies with Honours. A full literature review is provided in Lewis (2001).

Chapter 2: A comparison of alternative transport mechanisms

Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal organisms into the Southern Ocean

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Abstract

The introduction of invasive species may be the most profound modern threat to biological communities in high-latitude regions. In the Southern Ocean, the natural transport mechanism for shallow-water marine organisms provided by kelp rafts is increasingly augmented by plastic debris and shipping activity. Plastic debris provides additional opportunity for dispersal of invasive organisms, but dispersal routes are passive, dependent on ocean currents, and already established. In contrast, ships create novel pathways, moving across currents and often visiting many locations over short periods of time. Transportation of hull-fouling communities by vessel traffic thus poses the most likely mechanism by which exotic species may be introduced to the Southern Ocean.

Introduction

The impacts onnative communities associated with invasive organisms are now recognized as one of the primary threats to global biodiversity (Carlton 2001, Lubchenco *et al.* 1991, Hewitt 2003). While the majority of studies examining invasions focus upon impacts in the more populated regions and in highly modified systems, the problem of exotic organisms extends to even the most remote regions of the globe (Hines & Ruiz 2000, Orensanz *et al.* 2002, Gaston *et al.* 2003, Frenot *et al.* 2004).

A recent review of introductions in the Antarctic and sub-Antarctic region reports that at least 207 alien species have been recorded from high latitude ecosystems, which represent some of the most remote environments in the world (Frenot *et al.* 2004). The potential for the establishment of non-indigenous organisms in these relatively undisturbed environments is likely to increase due to the interaction of global climate change and expanding human interests (Chown *et al.* 1998, Chown & Gaston 2000, Stachowicz *et al.* 2002). International agreements, such as the Protocol on Environmental Protection to the Antarctic Treaty 1991 and the Convention on the Conservation of Antarctic Marine Living Resources 1980, have established very stringent standards of environmental stewardship for the Antarctic and the Southern Ocean, and prohibit many activities including the introduction of nonindigneous species. Nevertheless, vessel traffic and human visitation amoung the Southern Ocean and other regions still creates opportunities for unintended introductions (Whinam *et al.*, 2005), and since other threatening or destructive activities are prohibited, these invasions remain among the most profound modern threats to native biological communities.

Although invasions to high-latitude terrestrial ecosystems are now well described (Frenot *et al.* 2004, Whinam *et al.*2005), the same is not true for marine systems. Recent studies have suggested some potential mechanisms for marine introductions to sub-Antarctic and Antarctic coastlines including with rafts of marine debris (Barnes 2002, Barnes & Fraser 2003) and on vessel hulls (Lewis *et al.* 2003, Whinam *et al.* 2005), and there have been several recently documented occurrences of invasive marine organisms in the New Zealand sub-Antarctic islands (Cranfield *et al.* 1998) and the Antarctic Peninsula (Clayton *et al.* 1997, Tavares & De Melo 2004). Together,

these reports indicate that marine introductions can occur in these isolated regions and there is a need to examine further the biosecurity of the coastal marine ecosystems of the Southern Ocean.

Assessment of potential transport vectors for marine species in high-latitudes can provide valuable information regarding the hazard of biotic interchange for the future and could enable managers to focus resources towards the mitigation of this hazard. Although Salmonid fish were previously deliberately introduced to sub-Antarctic ecosystems (Davaine & Beall 1982, 1992; Cooper *et al.* 1992) and have become established in anadromous populations that may impact marine communities (Davaine & Beall 1982, 1992) , deliberate introductions are now prohibited by international agreement in the Antarctic Treaty Area (south of latitude 60°S), and are generally prohibited by similar domestic legislation instigated by the individual countries responsible for sub-Antarctic islands. Deliberate introductions, therefore, do not play the same role in this region as in other areas, and modern introductions are almost exclusively unintentional consequences of other human activities.

Two primary, anthropogenic, marine transport pathways have been identified for the Southern Ocean; oceanic vessel traffic (Lewis *et al* 2003, 2004) and drifting plastic debris (Barnes 2002, Barnes & Fraser 2003). The transfer of species aboard barges and other objects intended to be deployed in the marine environment are also possible pathways for marine introductions, but sound quarantine practices and targeted inspections may prevent biological transfer in association with these vectors (Whinam *et al.*, 2004). Plastics and vessel traffic can not be controlled in a similar fashion and do not present the same opportunities for quarantine barriers. This paper examines the relative significance of these two pathways and shows that transport in association with oceanic vessels should be the vector of primary concern for the transport of invasive organisms to high-latitude coastlines.

Biological communities associated with transport vectors

Ships' hulls and flotsam provide the most important anthropogenic surfaces for biological settlement in oceanic habitats. While ships' hulls represent only 24% of the total area of anthropogenic structures in the worlds oceans available for settlement, they carry over 85% of the total biomass associated with these structures (Railkin 2004). In contrast, flotsam, which accounts

for 70% of the total area of anthropogenic structures available for settlement, supports less than 6% of the total biomass (Railkin 2004). Therefore, although flotsam such as plastic debris presents a much greater surface area for colonization, the biomass carried by this vector is far lower than that carried by vessel hulls. These disparities are most likely a result of the largely oceanic nature of flotsam and consequently, the limited opportunity for settlement by coastal assemblages.

Vessels

Transport of marine organisms in association with ballast water has been the focus of much attention and is often considered the primary vessel-based form of non-indigenous species transport. Despite the large amount of ballast and associated biota transported around the globe each day, it has been suggested that ballast may not play an important role in the transport of non-indigenous biota to high-latitude coastlines (Lewis *et al.* 2003). This suggestion was based on the assumption that the typical pattern of activity of vessels used to support national Antarctic research programs results in a unidirectional (northwards) transport of ballast because fuel and cargo are offloaded in the Antarctic and ballast water (and associated biological communities) is taken on board in the Southern Ocean and is subsequently discharged directly into temperate ports.

In order to test the assumption that ballast is not a major biological transport pathway to high latitude regions, the ballast records of 43 Southern Ocean voyages that used Hobart as the first port of call following high latitude voyages from 1999–2001 were examined. These records include all vessels that visited Hobart as the first port of call following a voyage to Antarctica or the sub-Antarctic islands over this period. Within this timeframe, a total of 14 486 t of ballast water was drawn from various locations in the Southern Ocean and a total of 13 470 t was discharged (Figure 2.1). The home port, in this case Hobart, was the primary receiver of Southern Ocean ballast drawn from coastal regions in the Antarctic, and also from the sub-Antarctic islands. On only one occasion was temperate ballast water discharged at high latitude and the position recorded (184 t; 66°S, 145°E) but an additional 457 t was discharged at sea without location records. The mid-oceanic exchange of ballast is a precaution aimed at reducing the hazard of introducing species to coastal environments and is unlikely to introduce new species to coastal regions of the Southern Ocean (Hay & Tanis 1998, Endreson *et al.* 2004). Thirty visits were

made to Macquarie Island during the same three year period, but no ballast was released in the inshore coastal water here, or any other sub-Antarctic island.

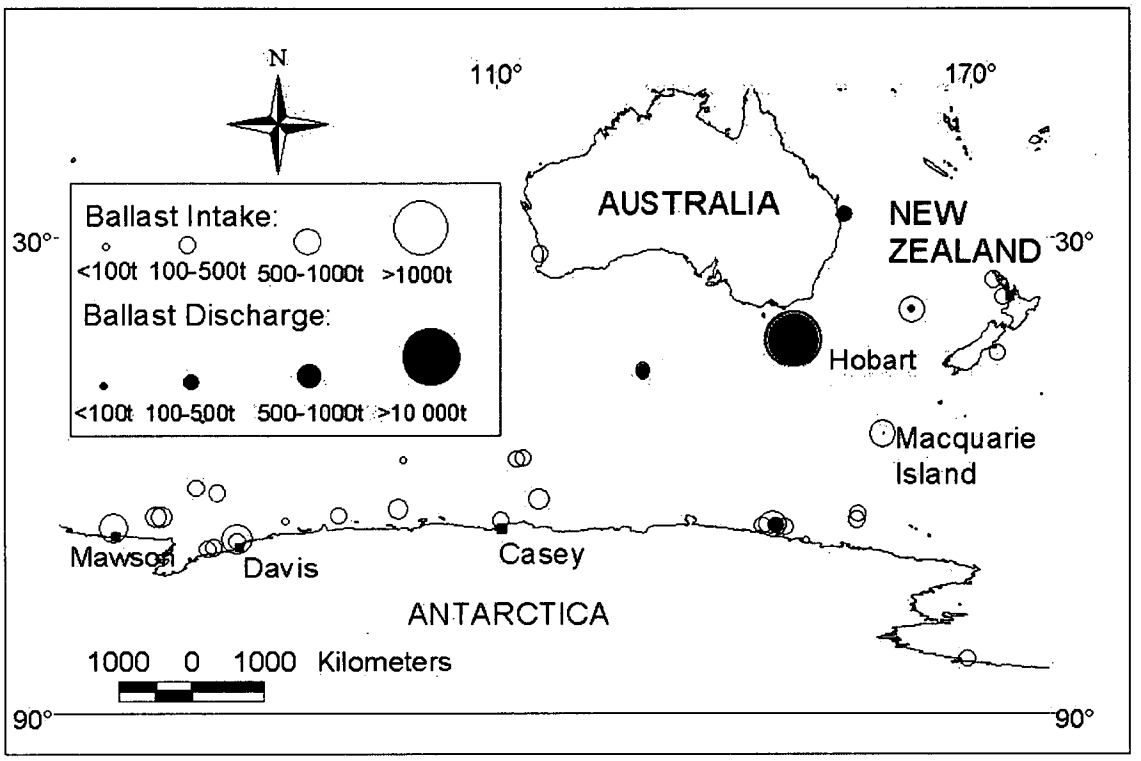

Figure 2.1: Patterns of ballast usage in the Southern Ocean recorded from vessels using Hobart as the first port-of-call following a high-latitude voyage. Ballast is generally entrained in Antarctic waters and discharged in the Port of Hobart.

Although transport of non-indigenous species with ballast water has been identified as a low hazard, Southern Ocean shipping still provides a mechanism for transfer of marine species in the form of the hull fouling communities, which thrive on ocean-going vessels. These assemblages, dominated by epibenthic species, may constitute the highest risk of introduction associated with vessels operating in the Southern Ocean. Although the rate of survival of fouling communities during oceanic transport has been little studied, it is recognised that fouling continues to play a major role in the transportation of non-indigenous species in the modern era (Rainer 1995, Hewitt, *et al.* 1999, James & Hayden 2000, Hewitt & Campbell 2001).

Recruitment of fouling communities on Southern Ocean vessel hulls can result in the formation of diverse assemblages of organisms (Lewis *et al.* 2003) (

Table 2.1). These communities include known invasive species entrained in temperate ports that are able to survive voyages to sub-Antarctic waters (Lewis *et al.* 2004).

Legitimate activities in the Southern Ocean, such as the operational support of science, legal fishing and Antarctic tourism, are well regulated under domestic legislation implementing international agreements. In addition, the tourism industry has initiated additional environmental precautions to ensure its sustainability under the voluntary industry body, the International Association of Antarctica Tourism Operators (IAATO 2002). In contrast, Illegal Unregulated and Unreported (IUU) fishing in the Southern Ocean operates outside the regulatory framework designed to promote sustainable fisheries activity and to avoid detrimental environmental impacts. The hulls of two IUU vessels, the *Viarsa* and the *Volga*, which were confiscated by the Australian Fisheries Management Authority after being apprehended while fishing illegally in Australia's Heard Island Exclusive Economic Zone were examined to determine the extent to which IUU vessels could contribute to the transport of biota (Table 2.1 – see Lewis *et al.* (2004) for methodology). The higher diversity of species recorded from the *Volga* may result from the longer (1month) period of port residency since detainment.

In addition to organisms transported by large vessels associated with national science operations and IUU fishing, biological assemblages were examined on the hull of a small (15 m) yacht *Tiama*, chartered for research in the New Zealand Auckland Islands (Table 2.1). Despite the well-maintained condition of this yacht, the fouling assemblage contained a total of 12 species including bryozoans, isopods, hydroids, barnacles and algae (Table 2.1). Six species, or 50% of the total community, are known to be invasive in some portion of their range (see references in Table 2.1). Of particular concern were the species attached to flaking paint fragments around the rudder of the vessel. Organisms attached to flakes of paint which are subsequently broken off in near-shore sub-Antarctic environments are introduced directly into the biological communities of these regions, and do not require the reproductive event that is normally essential for the liberation of invasive organisms from sessile, hull-fouling communities. While some species are able to regenerate following mechanical removal from the hull due to sheer force or abrasion (Carlton *et al.* 1995), individuals associated with detached paint flakes may be liberated as entire

and healthy specimens with an increased probability of survival and subsequent recruitment to the receiving site.

Table 2.1: Non-indigenous species observed on the hulls of 7 vessels operating in the Southern Ocean. Datum from the vessels *Southern Supporter* and *Aurora Australis* are taken from Lewis *et al.* (2004). Species are marked to indicate if they are introduced to Australia (*), cryptogenic in Australia (†), or considered invasive elsewhere in the world (§).

Taxa	RV *Aurora Australis*	RV *Southern Supporter*	*Sir Hubert Wilkins*	*Astrolabe*	*Viarsa*	*Volga*	*Tiama*	Reference
PLANTAE								
Alga								
Enteromorpha compressa	Y	Y						† Lewis, 1999
Enteromorpha intestinalis		Y			Y	Y	Y	† Lewis, 1999
Ulva rigida	Y		Y	Y				† Lewis, 1999
ANIMALIA								
ANNELIDA								
Polychaeta								
Hydroides ezoensis		Y						† Thorpe et al.,1987; § AMBS, 2002
Hydroides elegans						Y		* AMBS, 2002; § Hove, 1974; Bagaveeva et al., 1999
Sabella spallanzanii						Y		* Keough & Ross, 1999; § Hewitt et al., 2002[a]
Demonax leucaspis						Y		§ SERC, 2002[b]
ARTHROPODA								
Amphipoda								
Monocorophium acherusicum	Y	Y						* Poore & Storey, 1999; § Hewitt et al., 2002[a]
Monocorophium insidiosum					Y	Y		* Poore & Storey, 1999; § Hewitt et al., 2002[a]
Cirripedia								
Balanus amphitrite		Y			Y	Y		*§ Keough & Ross, 1999
Elminius modestus	Y		Y	Y			Y	† Keough & Ross, 1999; § Crisp, 1958
Decapoda								
Halicarcinus innominatus	Y		Y					* Pollard & Hutchings, 1990
CNIDARIA								
Bougainvillia muscus	Y						Y	*§ Watson, 1999
Clytia hemispherica		Y				Y	Y	*§ Watson, 1999;
Obelia dichotoma	Y							* Watson, 1999; § Cartlon, 1979;
Ectopleura crocea	Y					Y	Y	* Watson, 1999; § Cartlon, 1979; § Hewitt et al., 2002[a]
ENTOPROCTA								
Bugula flabellata	Y				Y		Y	* Allen, 1953; § Keough & Ross, 1999
Bugula neritina		Y			Y	Y		* Bock, 1982; § Hewitt et al., 2002[a]
Bugula stolonifera						Y		* Keough & Ross, 1999
Membraniopora membranacea	Y							* Keough & Ross, 1999: § Berman et al., 1992
Tricellaria occidentalis	Y				Y		Y	* Keough & Ross, 1999; § Dyrynda et al., 2000
Watersiporia subtorquata	Y	Y	Y		Y	Y		* Keough & Ross, 1999; § Carlton, 1979;
Schizoporella unicornis						Y		*§ Hewitt et al., 2002
UROCHORDATA								
Ascidiella aspersa						Y		* Keough & Ross, 1999; § Hewitt et al., 2002[a]
Styella plicata						Y		* Keough & Ross, 1999; § Hewitt et al., 2002[a]
Ciona intestinalis	Y		Y	Y				* Kott, 1985; § Hewitt et al., 2002[a]
Botrylloides leachi			Y			Y		* Keough & Ross, 1999; § Hewitt et al., 2002[a]
Botryllus schlosseri								* Keough & Ross, 1999; § Hewitt et al., 2002[a]
MOLLUSCA								
Mytilus galloprovincialis[1]	Y	Y	Y		Y	Y		† McDonald et al., 1991; § Hewitt et al., 2002[a]
Crassostrea gigas						Y		*§ Hewitt et al., 2002[a]
TOTAL SPECIES OBSERVED	**35**	**18**	**17**	**8**	**18**	**56**	**12**	
% NON-INDIGENOUS	**40**	**50**	**47**	**38**	**44**	**30**	**50**	

1. This species is known to be present on the Kerguelen Islands

Plastic Debris

The large-scale increase in the quantities of plastic debris being washed into coastal waters has been associated with various detriments to the environment including risks associated with ingestion of plastics, habitat degradation and chemical pollution through the decay of plastic materials (Coe & Rogers 1997, Derraik 2002). It has also been suggested that drifting plastics provide a substratum for the attachment of benthic organisms that may subsequently be transported to new regions through passive dispersal associated with wind and oceanic currents. Upon successful land-fall, these taxa may become invasive (Winston 1982, Winston *et al.* 1997, Derraik 2002, Barnes 2002, Barnes & Fraser 2003, Aliani & Molcard 2003).

While a large volume of literature describes the association of marine communities with vessel hulls and other anthropogenic structures (Skerman 1960, James & Hayden 2000, Railkin 2004), and fouling has been reported as the most significant vector in the introduction of invasive species to most areas of the globe (Pollard & Hutchings 1990, Cranfield *et al.*, 1998, Thresher 1999), little attention has been paid to the association of marine biota with drifting plastics (reviewed in Winston *et al.* 1997). The available literature indicates that a considerable range of species associate with drift plastics.

Bryozoans, in particular, have a propensity to colonize plastic drift and to dominate fouling communities (Winston 1982, Stevens 1992, Winston *et al.* 1997). For example, in a review of three studies examining the species found on plastic debris washed ashore in Florida, Winston *et al.* (1997) record more than 26 species of bryozoan amidst 64 species including nine phyla (algae, foraminifera, cnidaria, annelida, porifera, chordate (hemichordate), mollusca and crustacea). Despite this total diversity, only five pieces of drift plastic contained a community of more than 10 species and the large majority of 228 recorded items contained only a single species of bryozoan (Winston *et al.* 1997).

Other studies show a lower total diversity of fouling on plastic debris reflecting a lower number of items examined. Aliani & Molcard (2003) documented 22 macrobenthic species in a survey that included 14 samples of plastic debris collected from the Mediterranean. In a

study of recruitment to moored plastics, Stevens (1992) records over 90 species; this is higher than the species richness found on comparable quantities of drift plastic suggesting that factors associated with plastic debris in the oceanic environment may reduce the likelihood of settlement, or subsequent survival, of fouling taxa. For example, if an item of drift plastic spends the majority of time in open oceanic water this would reduce the likelihood of settlement by the shallow water, coastal benthic species that are most commonly found in fouling communities.

In the high latitude areas of the Southern Hemisphere, the incidence of debris-associated species is much lower than elsewhere (Barnes 2002). However, the tendency for bryozoans to dominate these assemblages appears to continue into the Southern Ocean. For example, five species of bryozoans were found in a community of 11 species fouling a single piece of plastic (Barnes & Fraser 2003). The diversity of organisms recorded by Barnes and Fraser (2003) is abnormally high for an item of drift plastic and indicates that it had been available for settlement for a long period of time. All the species described were endemic to the subantarctic location in which the plastic was found, indicating that colonization probably took place regionally. Thus, the presence of these species is not conclusive evidence that transportation of species is occurring over the large geographical distances required to facilitate biological introductions to the Antarctic region.

Communities associated with plastic drift items are often composed of species normally found in the local vicinity in which the item was recorded, or of species generally associated with natural drift items such as kelp rafts, and which are deposited on local coastlines by natural processes (Winston *et al.* 1997). Nethertheless, there are exceptions. For example, the bryozoan *Electra tenella*, which is not generally found in association with kelp rafts or hull-fouling communities, is found on plastic debris. Winston (1982) suggests that this potentially provides a mechanism for *Electra tenella* to extend its range, although it has not yet been reported from regions where it was previously unknown. Winston (1997) describes the delivery on plastics of individuals of a non-indigenous species of bryozoan washed ashore in Florida (*Thalamoporella evelinae*) and a species of oyster (*Lopha cristagalli*) washed ashore in southern New Zealand from where it had not been previously recorded (the species is known from the North Island of New Zealand). Thus, although no established, non-indigenous populations can be attributed conclusively to transport

by plastic debris, these observation demonstrate that transport by floating plastics beyond natural ranges does occur.

Transport directions

Vessel hulls and floating plastic both provide surfaces for the settlement of biological communities, yet the characteristics of these two vectors are very different. It is these differences that are likely to influence their potential to deliver non-indigenous species to new locations. The key question determining the relative hazard presented by different vectors is whether or not they create a new transport pathway between locations that were not previously connected by natural mechanisms or, alternatively, whether they simply augment a connection that was already established. Despite the open nature of the world's oceans and the connectivity of regions created by the ocean's circulation system, the scale of transport enabled by human vessel traffic provides new opportunities for direct and rapid transport of organisms in directions that are contrary to typical oceanic currents. Floating plastic is an increasing and persistent presence in the environment. However, the restriction of this vector to natural transportation on wind and ocean currents, with no opportunity for rapid delivery of organisms, means that plastics simply provide the potential for increased transport between locations using mechanisms already available to natural vectors such as kelp, pumice and wood.

Oceanic shipping crosses major biogeographical barriers in order to transport humans to desired locations. As an example of the nature of biological transport enabled by shipping in the Southern Ocean, historical traffic has provided links between the sub-Antarctic Macquarie Island and ports as distant as London and Russia (Cumpston 1968). Modern visitation to the island comes from three main, last-port-of-call regions: Australia, New Zealand and Antarctica. However, several of the vessels traveling to the sub-Antarctic islands and the Southern Ocean also operate in the northern hemisphere for part of the year and may thus facilitate transport of boreal communities. Tasmania and New Zealand supply the bulk of modern traffic (Fig. 2) because of national science programs operating out of Hobart, and the popular tourism pathway that runs between Hobart, New Zealand and the sub-Antarctic islands.

Opportunities for biological transport to the eastern section of the Antarctic continent are limited due to the removal of biological material from exposed surfaces of ships' hulls during the passage through substantial sea ice required to approach shore (Lewis *et al.* 2004). As a result, northward traffic to the sub-Antarctic islands coming from eastern Antarctica is also unlikely to create a significant hazard for biological transfer. However, vessels traveling southward to ice-free sub-Antarctic islands from the temperate ports of Hobart (Australia), Bluff and Lyttelton (New Zealand) may spend extended periods in temperate ports prior to departure, particularly at the start of the season, and as vessels do not pass through sea-ice during transit to the sub-Antarctic, fouling communities are not exposed to the same mechanical damage that removes organisms during visits to the Antarctic continent. Likewise, the avoidance of significant sea ice by tourism and fisheries operators in the Antarctic Peninsula region may facilitate the biological transport to the Antarctic continent in this area. As a result voyages that pass directly from temperate ports to sub-Antarctic islands and operations in the Antarctic Peninsula region are considered to pose a high hazard of biological transport.

In contrast to the active pathway created by vessels, transport associated with floating plastics is passive and determined by natural currents. Figure 2.2 shows the natural oceanic currents in the sub-Antarctic region of Macquarie Island and indicates the direction that biological transport is likely to take in association with plastics and with modern vessel activity. Vessels provide a mechanism for dispersal of organisms that would not be possible by natural processes such as long-lived planktonic larvae, or by association with natural drift objects. Despite their relative persistence in the marine environment and the documented increase in the quantity of plastic debris, drift plastics do not represent a novel route for the transport of biological communities, but act as an anthropogenic supplement to a natural dispersal pathway. Indeed, at least across sub-Antarctic latitudes, the role of dispersal by floating debris may be insignificant in comparison to that provided by kelp rafts. Kelp raft surveys between Hobart and Macquarie Island indicate an average of 3.7 kelp rafts km^2 of ocean, which extrapolates to over 70 million rafts afloat at any one time across this band of the Southern Ocean (Smith 2002). The kelp habitat, and in particular the holdfast, supports diverse assemblages of invertebrate species at all sub-Antarctic islands (Smith & Simpson 1995, 2002) and transport by detached kelp has been hypothesized to explain the present circum-sub-Antarctic distribution of a number of taxa (Knox & Lowry 1977, Helmuth *et al.* 1994).

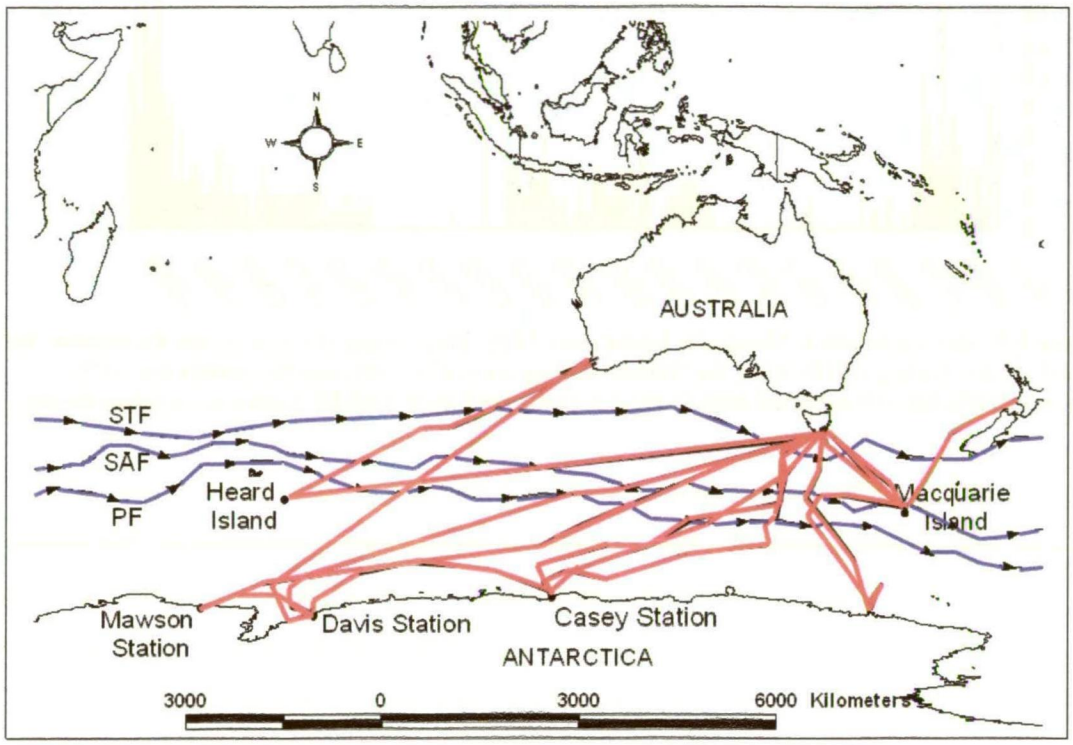

Figure 2.2: Direction of transport enabled by the operation of floating plastics and vessel hulls acting as vectors for the delivery of non-indigenous organisms. Plastics are restricted to unidirectional (west to east) transport in association with the west wind drift (→), and are restricted in the north-south plane by the existence of frontal regions (STF = Subtropical front; SAF = sub-Antarctic front; PF = Polar front). Vessel tracks (—) are a selection of voyages undertaken between 2002-2004 to demonstrate some of the common shipping lanes.

Delivery of Propagules

Fouling communities have been shown to be capable of surviving journeys to sub-Antarctic latitudes (Lewis *et al.* 2004) and the likelihood of introductions will increase as the number of ship visits increases. Three peaks in shipping activity to Macquarie Island have occurred since its discovery in 1810 (Figure 2.3). The first (1810–80) was associated with the initial exploitation of seals, and the second (1880–1950) was associated with a second period of exploitation commonly referred to as the "Hatch" sealing era (Cumpston 1968). A final, larger, peak associated with the Australian National Antarctic Research Expeditions (ANARE) scientific exploration, and with the growing tourism industry, is obvious over the period 1950–present. This recent peak is likely to continue to rise as tourism in the region grows (Frenot *et al.* 2005).

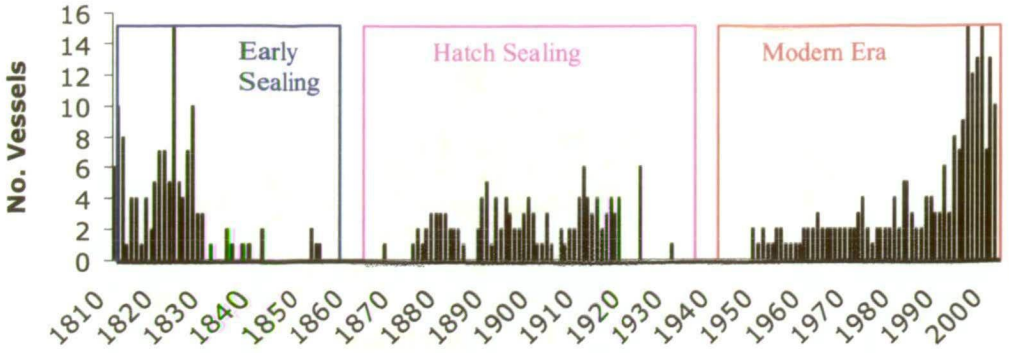

Figure 2.3: Ship visitations to Macquarie Island since 1810. Three peaks of visitation are discernable: the period of early sealing (1810-1860), the "Hatch" sealing era (1870-1940) and the modern era (1950 – present). Traffic records extracted from Cumpston (1968) and from ANARE historical visitation records.

Even though ship traffic has increased significantly in recent years, at a maximum of only 15 visits per year, it is still remarkably low compared to mainland ports. For example, Port Phillip Bay currently receives over 3000 visits per year (Joanne Weinert, AQIS, personal communication, 2004). From shipping records, it can be estimated that the total number of ship visits to Macquarie Island since its discovery numbers ≈ 458 ((Figure 2.3). Over the past decade tourism (51%) has been the reason for most ship visits to Macquarie Island (Figure 2.4), followed by science (26%) and fisheries (13%). Although the total volume of traffic is low, without precautionary measures, the risk of marine introductions can only increase as the number of visits per year increases

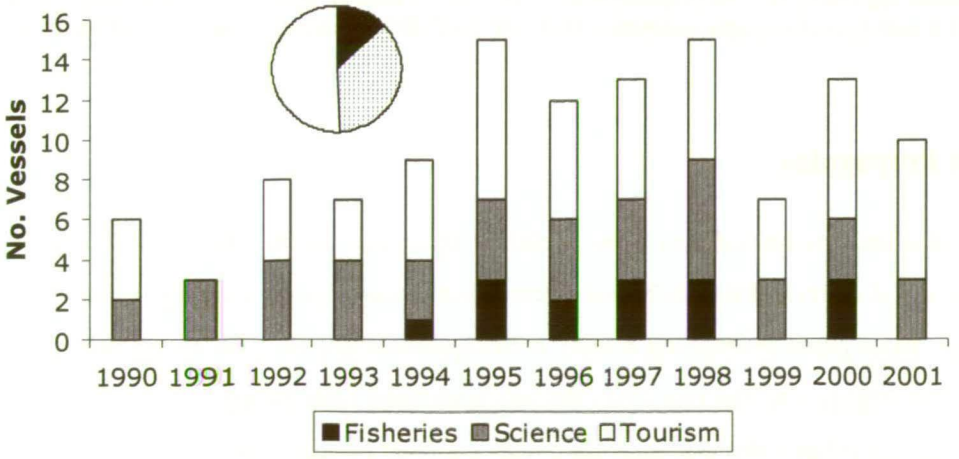

Figure 2.4: Purpose of vessels visiting Macquarie Island in the period 1990-2001. The pie graph displays total visitation proportions for this period and indicates that tourism provides the bulk of traffic.

Conclusions

Transport in association with floating plastic debris (Barnes 2002, Barnes & Fraser 2003), and biological transfer via vessel traffic (Lewis *et al.* 2003) have been suggested as possible mechanisms for the transfer of non-indigenous marine organisms to sub-Antarctic coastal waters in the Southern Ocean. Rubbish of human origin is unlikely to have doubled or tripled the rafting opportunities for biota as suggested by Barnes (2002). While plastics in the environment have increased in abundance, and they do offer a viable and persistent surface for colonisation, several properties of plastic debris serve to limit the potential for this transport pathway to effectively deliver new species to high latitude coastlines. Specifically, most plastics in high latitude regions are sourced from refuse dumped in mid-ocean regions by fishing activities and thus offer a transport mechanism for cosmopolitan pelagic species rather than coastal communities likely to represent a hazard of invasion. Furthermore, the passive dispersal of plastic flotsam means that rather than offering a novel pathway, this vector acts to supplement existing natural pathways. Kelp rafts are abundant and provide a natural transport mechanism, which presumably has been available since the initial establishment of kelp communities on sub-Antarctic islands. Drifting plastics thus represent a small addition to the opportunity for transport already provided by kelp rafts and other natural floating materials such as pumice and wood.

In contrast, fouling on vessel hulls creates entirely new transfer pathways for biological communities across substantial biogeographical barriers. The nature of shipping is such that it can result in the rapid transfer of established assemblages directly from one coastal region to another. Marine invasive species of concern are almost exclusively shallow coastal species (Hewitt *et al.* 1999, Carlton 2001, Railkin 2004). In the Southern Ocean, fishing is by far the greatest source of marine debris, including fishing gear and rubbish discarded from fishing boats (Slip & Burton 1991, Eriksson & Burton 2001, Burton & Schulz 2001). Much of this material will have entered the sea in open ocean locations. It is not known what proportion of marine debris eventually reaches coastal waters but, clearly, only a sub-set of the marine debris in the ocean will move from one shallow coastal area to another. This is not the case for ships. Almost all shipping traffic is from one coastal location to another, thus there is the potential for rapid transfer of obligate, shallow water species between coastal areas.

If the integrity of Southern Ocean biodiversity is to be conserved, it is essential that pathways for marine introduction are understood, and, where appropriate and necessary, management measures be initiated to limit biotic transfer. These should include the acquisition of baseline data to ensure that alien species are recognized as such, and long-term monitoring programs. However, the latter will only indicate whether an incursion has taken place and response guidelines are essential if there is to be any attempt to control an incursion. Experience in other parts of the world indicates that invasive species, particularly marine invasives, once established, are difficult and expensive to control (McEnnulty *et al.*, 2001). Thus, the only effective method is to reduce the opportunities for incursion – this requires a good understanding of the likely pathways. The most likely scenario for future marine invasions in the Southern Ocean is that the natural barrier to dispersal will be breached by species transported in hull-fouling.

Acknowledgements

We are grateful for the provision of ballast water data by the Australian Quarantine and Inspection Service (AQIS), and the assistance and advice of the Australian Fisheries Management Authority (AFMA) who provided access to confiscated IUU fishing vessels and Southern Ocean fisheries information. We also acknowledge the assistance and cooperation of P&O Polar shipping and Beaufort Shipping and the skippers of all vessels inspected in this study. We thank the New Zealand Ministry of Fisheries for providing funds for the inspection of fouling communities on *Tiama*, and the New Zealand Department of Conservation who provided logistic support. We appreciate the constructive criticism and input of the reviewers of this paper, in particular David Barnes, who caused us to review many of our ideas and provided support and encouragement in the interests of rigorous scientific debate.

Chapter 3: Management of toxic paints or invasive pests?

A management quandary: toxic paints or invasive pests

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Abstract:

The discovery of high levels of tributyltin compounds in Antarctic marine sediments has prompted managers to consider the banning of such substances in this region. The banning of anti-fouling coatings may result in an increase in the risk of non-indigenous species invasions. Our studies show that untreated vessels carry a more diverse community of fouling organisms than treated hulls on which fouling is restricted to specific untreated interstices. Up to 40% of the species recruited to the hulls of Southern Ocean vessels are species with invasive histories. Viable fouling assemblages can survive prolonged voyages to high-latitude coastlines, yet passage through sea-ice may remove fouling communities due to mechanical abrasion reducing the hazard of introductions to ice-bound coastlines. The banning of anti-fouling compounds may be of particular concern for the ice-free sub-Antarctic islands which represent a common anchorage point for vessels en-route to Antarctica.

Introduction:

The discovery of high levels of tributyltin (TBT) and associated compounds in the marine sediments of the Antarctic shelf by Negri *et al.* (2004) raises some urgent questions for the management of shipping in this remote and relatively undisturbed environment. The impacts onmarine communities associated with toxic anti-fouling compounds such as TBT have been well described (see review by Fent, 1996). Concern over their impacts has resulted in international agreement to ban the use of TBT under the International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS 2001). This convention will not enforce the ban on vessels owned by governments. Excluded are navy ships and other vessels owned and operated by governments, including the ice-breakers used to support many national Antarctic programs. Despite this exclusion, some governments have indicated they will voluntarily discontinue TBT antifouling paint use on government owned ships. Negri *et al.* (2004) question whether these measures are sufficient by asking if the use of antifoulant biocides on ships entering Antarctic waters should be addressed by the Antarctic Treaty system.

The purpose of this contribution is to consider some of the issues raised by Negri *et al.* (2004) and to broaden the discussion by suggesting additional factors for consideration when deciding on appropriate hull treatments for vessels operating in the Southern Ocean.

While a ban on biocidal agents in vessel coatings for high-latitude systems would reduce the impact of this particular exogenous threat to Antarctic and sub-Antarctic systems, such a ban is also likely to result in increased levels of hull fouling, which could increase the potential for transfer of non-indigenous (NIS) species in hull fouling assemblages. Globally, invasive species are considered one of the primary threats to native biological diversity, equal to the threat posed by human mediated global climate change (Carlton, 2001; Hewitt, 2003). Although marine introductions have not yet been identified as a major issue in high-latitude waters, several species are suspected of being introduced to the Antarctic Peninsula region (Clayton *et al.*, 1997; Tavares & De Menlo, 2004) and to the New Zealand sub-Antarctic islands (Cranfield *et al.*, 1998). In addition, it is demonstrated that modern shipping activities to Antarctic waters can carry diverse fouling assemblages that may result in introductions to Southern Ocean coastlines (Lewis *et al.*, 2003).

The fouling assemblage associated with two vessels operating in the Southern Ocean; one with an antifouling paint (R.V. Southern Supporter) and one without (R.V. Aurora Australis) were recently examined. Divers surveyed the hulls of both vessels immediately before and after voyages of several weeks duration. Distribution of fouling communities was assessed through the use of 10 replicate 0.1 m^2 photo-quadrats at several depths. Due to a shallower draft, RV Southern Supporter communities were only sampled at 3 depths (1 m, 4 m, 6 m) while RV Aurora Australis communities were sampled at 4 depths (1 m, 4 m, 6 m, 8 m). Percent cover data was calculated from the photo-quadrats using Image J software. Our results are relevant to the discussion on biocidal hull treatments because they illustrate the effects of passage through sea ice on hull fouling assemblages.

The hull of *R.V. Aurora Australis* was surveyed in Hobart on 2 September 2003 before it departed for the first voyage of the Antarctic season after a winter laid up in the Port of Hobart. The ship conducted marine scientific research in the sea-ice zone before moving to Australian Casey Station (66º15'S) to transfer scientific and support staff. Both activities involved transit through sea-ice, with ice conditions (Table 3.1) to a maximum of 10/10 cover and up to 1.0m deep first year ice with up to 0.4m snow cover (Ian Allison, pers. comm., daily ship report). On return the hull was resurveyed in Hobart on 30 October 2003.

Table 3.1: Conditions during the two Southern Ocean voyages (from daily ship reports) * Temperature ranges at points of departure are based upon 1986-1999 Sea Surface temperatures from the IMCRA bioregions of the ports (A Hobday, pers comm.).

	R.V. *Aurora Australis*	R.V. *Southern Supporter*
Source Port	Hobart, Tasmania	Fremantle, Western Australia
Southern Ocean Destination	Casey Station, Antarctica	Heard Island, Sub-Antarctic
Recipient Port	Hobart, Tasmania	Hobart, Tasmania
Direct distance (Source Port/Destination/Recipient Port) (km)	6886	9510
Voyage duration (days)	52	28
Maximum ship speed (knots)	14.5	12.5
Maximum wind speed (knots)	44	40-45
Minimum water temperature (°C)	-1.8	1
Temperature range at point of departure (°C)*	Hobart: 9.0 - 20.1	Fremantle: 16.5– 27.5
Maximum sea-ice	10/10 cover >1.0m deep 0.4m snow cover	None

Table 3.2: Species diversity and distribution observed on the hulls of the vessels R.V. Aurora Australis and R.V. Southern Supporter. Species with a range in the Southern Ocean are identified, and those considered invasive in portions of their range are underlined and references marked to indicate whether they are introduced to Australia (*), cryptogenic in Australia (†), and considered invasive elsewhere in the world (§).

Taxa	Presence in Southern Ocean	Attached (A) / Unattached (U)	*R.V. Aurora Australis* 02.09.03	*R.V. Aurora Australis* 30.10.03	*R.V. Southern Supporter* 31.11.03	*R.V. Southern Supporter* 30.12.03	Reference
PLANTAE							
Alga							
Bryopsis sp.		A			Y	Y	
Cladophoropsis sp.		A			Y	Y	
Enteromorpha compressa	Y	A	Y	-	Y	Y	† Lewis 1999
Enteromorpha intestinalis	Y	A			Y	Y	† Lewis 1999
Ulva rigida	Y	A	Y	-			† Lewis 1999
Seagrass							
Ruppia magnacarpa		A	Y	-			
ANIMALIA							
ANNELIDA							
Polychaeta							
Harmothoe sp		U	Y	-			
Hydroides ezoensis		A			Y	Y	† Thorpe *et al.* 1987 § AMBS 2002
Polychaete sp1		A	Y	-			
Pomatocerus taenata		A	Y	-			
ARTHROPODA							
Amphipoda							
Caprellid sp1		U			Y	Y	
Corophidae sp.1		U	Y	-			
Corophidae sp.2		U	Y	-			
Monocorophium acherusicum		U	Y	-	Y	Y	* Poore & Storey 1999 § Hewitt *et al.* 2002
Hyallidae sp.1		U	Y	-			
Hyallidae sp.2		U	Y	-			
Hyperrid sp.		U			Y		
Ischyroceridae sp.1		U	Y	-			
Jassa falcate		U			Y		
Jassa herdmani	Y	U				Y	
Jassa sp.		U	Y	-			
Cirripedia							
Balanus amphitrite		A			Y	Y	*§ Keough & Ross 1999
Balanus variegatus		A			Y	Y	
Chonchoderma aurita	Y	A				Y	
Elminius modestus		A	Y	-			† Keough & Ross 1999 § Crisp 1958
Lepas anitifera		A			Y	Y	
Decapoda							
Halicarcinus innominatus			Y	-			*Pollard & Hutchings 1990
Machrobranchium sp		U	Y	-			

Taxa	Presence in Southern Ocean	Attached (A) / Unattached (U)	*R.V. Aurora Australis* 02.09.03	*R.V. Aurora Australis* 30.10.03	*R.V. Southern Supporter* 31.11.03	*R.V. Southern Supporter* 30.12.03	Reference
CHORDATA							
Teleost							
Larval fish sp		U	Y	-			
CNIDARIA							
Fa. Plumulariidae		A				Y	
Fa. Campanulariidae		A	Y	-	Y		
Bougainvillia muscus		A	Y	-			*§ Watson 1999
Clytia hemispherica		A			Y	Y	*§ Watson 1999
Obelia dichotoma		A	Y	-			* Watson 1999 § Carlton 1979
Obelia sp		A	Y	-			
Ectopleura crocea		A	Y	-			* Watson 1999 § Carlton 1979; Hewitt *et al* 2002
ECTOPROCTA							
Bugula flabellata		A	Y	-			* Allen 1953; Pollard and Hutchings 1990 § Keough and Ross 1999
Bugula neritina		A			Y		* Bock 1982 § Hewitt *et al.* 2002
Celleporina sp		A			Y		
Electra sp		A	Y	-			
Membranipora membranacea		A	Y	-			* Keough and Ross 1999 § Dufrense 1992
Tricellaria occidentalis		A	Y	-			* Keough and Ross 1999 § Gordon and Mawatari 1992; 1992; Dyrynda *et al* 2000
Watersiporia subtorquata		A	Y	-	Y	Y	* Keough and Ross 1999 § Carlton 1979; Gordon and Mawatari
UROCHORDATA							
Ascidian sp 1		A	Y	-		Y	
Ascidian sp2		A	Y	-		Y	
Ascidian sp3		A	Y	-		Y	
Ascidian sp4		A	Y	-			
Ciona intestinalis		A	Y	-			*§ Kott 1985; Hewitt *et al* 2002
MOLLUSCA							
Mytilus galloprovincialis	Y[1]	A	Y	-	Y	Y	† McDonald *et al* 1991; Hewitt *et al* 2002 § Stewart Grant & Cherry 1985; Hewitt *et al* 2002
Nudibranch sp.1		U	Y	-			
Nudibranch sp.2		U	Y	-			
TOTAL			35	0	18	19	
% Non-indigenous			40	-	50	42.1	

1 - this species is known to occur in the Kerguelen Islands

The pre-departure survey provided additional evidence of the diversity of fouling assemblages that can recruit to untreated hulls (see Table 3.2). Included in the 35 species recorded from the fouling assemblage were 13 species (40%) known to have invaded new coastal regions through an association with human transport vectors. Whilst fouling covered in excess of 80% of the hull surface in some locations prior to departure (Table 3.3), no fouling remained following the journey through sea-ice. This finding suggests that mechanical stress resulting from the passage through sea-ice cleaned the hull of fouling assemblages during the voyage and it is likely that the hull was clean prior to reaching Antarctic coastal waters.

The hull of the *R.V. Southern Supporter* was examined in the Port of Fremantle, Western Australia on 31 November 2003 before departing on a four week voyage to Heard Island (53º05'S). The voyage to Heard Island does not require transit through sea-ice but involves passage through some of the roughest seas in the world. On this occasion the ship experienced several days of very rough seas, heavy swells and winds up to 45 knots (Robb Clifton pers. comm. daily ship report). On the return of the ship to Hobart on 30 December 2003 the hull was re-examined.

In contrast to the diverse assemblages recorded on the untreated hull of the *R.V. Aurora Australis*, the assemblage on the treated hull of the *R.V. Southern Supporter* before departure was much less diverse (18 spp.; Table 3.2). Consistent with other studies on the efficiency of antifouling treatments (Railkin, 2004) most of the species were found on untreated parts of the hull such as the cathodic protection systems, which are deliberately left unpainted, and the areas covered by supporting chocks during re-painting in dry-docks, referred to as dry-dock support strips (DDSS; Coutts, 1999; Lewis, *et al.*, 2003).

After the voyage to Heard Island a large proportion of the species in the original fouling assemblage remained (Table 3.2). 13 species or 72% of the original assemblage survived the journey, including eight species known to be invasive. All surviving species were restricted to the untreated areas of the DDSS and cathodic protection systems. The presence of these species at the beginning and end of the voyage shows that viable individuals were present on the hull when the vessel was in the waters adjacent to Heard Island. This is of particular concern because Heard Island is one of the few invasion-free environments remaining in the world; one of the values for which it was inscribed to the World Heritage List in 1997. In addition, not only did a significant

portion of the original Fremantle assemblage survive the journey to Hobart via Heard Island intact, but at the end of the voyage an additional six species were detected, many native to the Southern Ocean.

Table 3.3: The distribution and dominant taxa observed at initial and final inspections of hull fouling communities for a) RV Aurora Australis, and b) RV *Southern Supporter*. Distribution was assessed through the use of 10 replicate 0.1m^2 photo-quadrats at each depth. Note that large standard deviations recorded for the RV *Southern Supporter* communities correlate to the patchy distribution of barnacles at 1m depth, the restriction of algal communities to cathodic protection installations at 4m, and the restriction of fouling to DDSS at 6m. Smaller standard deviations in the RV *Aurora Australis* community reflect a more uniform distribution of organisms.

a) *R.V. Aurora Australis* (without antifouling)

	Before 2.09.03		*After* 30.10.03		
Depth (m)	% Fouling Cover	Dominant Taxa	% Fouling Cover	Dominant Taxa	Notes
1	80.9 (10.3)	Algae	0	-	Species were evenly distributed at each depth of the hull surface. No species were observed from the hull of the *R.V. Aurora Australis* following the return of this voyage.
4	71.7 (7.9)	Algae	0	-	
6	17.6 (6.4)	Ascidians, Polychaetes	0	-	
8	28.3 (14.3)	Ascidians	0	-	

b) *R.V. Southern Supporter* (with antifouling)

	Before 31.11.03		*After* 30.12.03		
Depth (m)	% Fouling Cover	Dominant Taxa	% Fouling Cover	Dominant Taxa	Notes
1	0.7 (1.5)	Cirripedes	0.6 (1.2)	Cirripedes	Few barnacles distributed on hull surface
4	1.8 (4.8)	Algae	2.6 (3.8)	Algae	Communities restricted to cathodic protection devices
6	9.7 (19.2)	Polychaetes, Cirripedes	12.1 (24.4)	Polychaetes, Cirripedes	Communities restricted to DDSS

Discussion

The difference between fouling communities after the voyages to the Antarctic continent and Heard Island are strong evidence that passage through sea-ice is the cause of the loss of the fouling assemblage, probably due to abrasion. Ice abrasion is likely to be the primary cause of the loss of the fouling community because of the strong sheer forces associated with pushing through sea-ice during ice-breaking operations. Alternative explanations such as faster traveling speeds, rougher seas or colder water were rejected because none of these factors differed greatly between the two voyages (Table 3.1).

Our results demonstrate that the benefits of using biocidal paints on external hull surfaces to reduce the risks of introductions may be largely negated for vessels operating in sea-ice. Negri and others (2004) suggest that the introduction of TBT compounds to Antarctic sediments does not occur through slow leaching processes, but probably results from a similar process of abrasion of paints during passage through sea-ice; a process which may introduce flakes of paint directly into the waters adjacent to major shipping lanes. This process significantly reduces the effectiveness of the antifouling paint themselves, by leaving large chips and scrapes in the coating that allows the settlement of fouling organisms (pers obs).

Epoxy coatings may be more durable and last longer than anti-fouling paints when used on the hulls of ice-breakers. Instead of biocidal paints, the *R.V. Aurora Australis* is coated with a durable epoxy (Hempadur Multistrength 4575), and biocidal agents (Hepadur Multistrength 4575 – a self polishing antifoulant with cuprious oxide, diuron and liquid hydrocarbon as the active agents) are restricted to the sea-chests and the bow-and stern thrusters which are not subject to ice abrasion. Lewis *et al.* (2003) demonstrate that due to the absence of antifouling compounds upon the *R.V. Aurora Australis* hull, diverse biological assemblages, including species with known invasive capabilities, settle on the hull during periods of inactivity over winter.

Some species, such as the Australian native hydroid *Ralpharia magnifica*, have been shown to settle in substantial assemblages only two weeks after passage through sea-ice (Lewis *et al.*, 2003). As a consequence, anti-fouling coatings may still both reduce the risk of transfer of invasive

marine species and increase the operational efficiency of vessels due to the reduced tendency of vessel hulls to accumulate fouling organisms during periods of inactivity in temperate ports.

Whether or not the application of anti-fouling treatments would confer an operational or economic benefit depends entirely on how the ship is used. There is little value in treating those ice-breakers that are based in southern hemisphere ports and are only used to support activities on the Antarctic continent. The reduction in maximum speed and fuel efficiency caused by a heavily fouled hull only lasts until sea-ice is first encountered during the first voyage of the Antarctic season. The cost of anti-fouling treatments is unlikely to be off-set by increased fuel efficiency during this brief period. However, for ships based in the northern hemisphere or involved in Antarctic voyages for only part of the year, such as many ice-breakers used for tourism, the operational benefits of anti-fouling treatments may be much greater. A fouling layer of only 1mm thickness can cause a 15% loss in ship speed, and fouling may result in a 36% increase in fuel consumption (Walters, 1996). This increased efficiency could generate a substantial cost saving during a relocation voyage from the northern hemisphere.

Similarly, the environmental benefits of either using or not using an anti-fouling treatment will also depend on how the ship is operated. While antifouling paints may cause toxic impacts onbenthic communities in the near-shore Antarctic marine environment, they also reduce the chance of transfer of non-indigenous species under certain circumstances. For those ships based in southern hemisphere ports and only traveling to the Antarctic continent there appears to be no environmental benefit to the use of antifoulants and there is the potential risk of toxicants entering the environment. However, shipping activities in the Southern Ocean often involve multiple shore approaches which may include anchoring in nearshore waters of sub-Antarctic islands. Both tourism operators and scientific research and re-supply vessels routinely visit sub-Antarctic islands en-route to Antarctic coastal waters. For ships that are used in this way the environmental benefits of not using biocidal antifoulants must be balanced against the increased hazard of marine introductions, particularly to sub-Antarctic islands.

The introduction of toxic substances to the pristine waters of the Antarctic continental shelf is manifestly undesirable, yet the introduction of invasive marine organisms may have a far more profound and long-lasting influence upon high latitude marine communities (Grosholz, 2002).

While pollution by TBT and other biocidal compounds are localized and will decrease with time, invasive populations of marine organisms are capable of maintaining, and subsequently increasing their density and impacts following establishment. Furthermore, upon introduction in areas adjacent to shipping activity, populations of invasive organisms are capable of spreading laterally away from the site of initial infestation and affecting communities remote from any human disturbance (Orensanz *et al.*, 2002; Wasson *et al.*, 2001). As an extreme example of lateral spread, populations established at one sub-Antarctic island could be capable of spreading to down-stream islands through an association with kelp rafts (Edgar, 1987; Smith, 2002) or floating plastic debris (Barnes, 2002; Barnes & Fraser, 2003), both of which have been shown capable of dispersing coastal organisms between sub-Antarctic islands in association with the circum-Antarctic currents.

Due to a combination of rapid climate change and an increase in the intensity of human operations in the Southern Ocean, the risk of marine introductions in this region will increase in the future (Chown *et al.*, 1998; Chown & Gaston, 2000; Convey, 2001; Stachowicz *et al.*, 2002; Frenot *et al.*, 2004). While the threat of TBT compounds and other toxic agents used in antifouling paints needs to be addressed in high latitude systems, caution is urged in the consideration of any measures aimed to limit the use of antifouling agents in Southern Ocean waters. Any move to do so must carefully weigh the potential side-effects, and should consider the secondary impacts onthe sub-Antarctic islands which are connected to the Antarctic coastal waters through common shipping pathways.

Chapter 4: An alien marine community travels to Macquarie Island

Barging in: a temperate marine community travels to the sub-Antarctic

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Abstract

A diverse fouling community discovered encrusting a barge intended for deployment at sub-Antarctic Macquarie Island is described. The barge's role as a transport vector for NIS marine organisms is discussed. The barge proved to be a potential vector capable of transporting entire epi-benthic communities, 20 species in total, from a temperate estuarine system (Derwent River, Tasmania, Australia) into the sub-Antarctic. For one invasive amphipod species *Monocorophium acherusicum*, over 136 000 individuals including ovigerous females were calculated to be associated with the barge fouling community. Although distinct differences exist between the thermal ranges of Macquarie Island and the Bruny bioregion of Tasmania, a hazard assessment based on the Gower similarity co-efficient suggested sufficient similarity between the two environments to allow for survival of transported organisms during eight months of the year. Several invasive species are able to survive the thermal conditions of the sub-Antarctic irrespective of the time of year. This study identifies the need for effective quarantine measures aimed at identifying and managing marine biosecurity hazards in association with human activities in high latitude regions.

Introduction

The establishment of invasive organisms in the sub-Antarctic islands is recognized as one of the foremost threats to native communities in this region (Lewis *et al.* 2003; Lewis *et al.* 2005; Frenot *et al.* 2005). Quarantine measures are relied on to limit the influx of biological material from temperate regions into sub-Antarctic and Antarctic environments (Frenot *et al.* 2005; Whinam *et al.* 2005), and also to prevent the transfer of pathogens and material between islands and regions (Kerry *et al.* 1999). Over the last decade stringent codes of quarantine have been developed by many national operators in the Southern Ocean, however procedures are generally aimed at controlling the movement of terrestrial material such as seeds and invertebrates in association with expeditioners, equipment and food. Little consideration as yet has been provided towards marine biosecurity and the transport of exogenous aquatic organisms associated with materials intended for deployment in the marine environment.

Currently identified transport pathways for marine introductions such as vessel traffic (Lewis *et al.* 2003; Lewis *et al.* 2005a; Lewis *et al.* 2006) and plastic debris (Barnes 2002; Barnes and Fraser 2003; Barnes and Milner 2005) offer little opportunity for the instigation of voyage specific quarantine measures and require a re-appraisal of general shipping operations and a greater awareness of the impacts associated with marine pollution. In contrast, science and re-supply operations in the sub-Antarctic islands frequently introduce small vessels, ropes, barges, scientific equipment and other material into the marine environment. These objects, which are stored aboard the larger re-supply vessels during transit, offer ample opportunity for screening for potential exogenous organisms and the application of standardised cleaning protocols

This report describes an intact and viable marine community, including several invasive organisms, fouling a barge intended for deployment at the sub-Antarctic Macquarie Island (Figure 4.1). Although prompt action by science personnel identified the biological hazard associated with this community (Whinam *et al.* 2005), and operation personnel immediately took action to reduce the risk (including steam cleaning and the non-deployment of the barge), the discovery was largely a matter of serendipity and demonstrates the need for constant vigilance and formal quarantine guidelines. An analysis of the composition of the community and associated risks indicates the existence of a viable transport pathway. A basic awareness of

simple quarantine precautions must be applied to such objects to ensure that they do not carry entrained biological assemblages into sub-Antarctic environments.

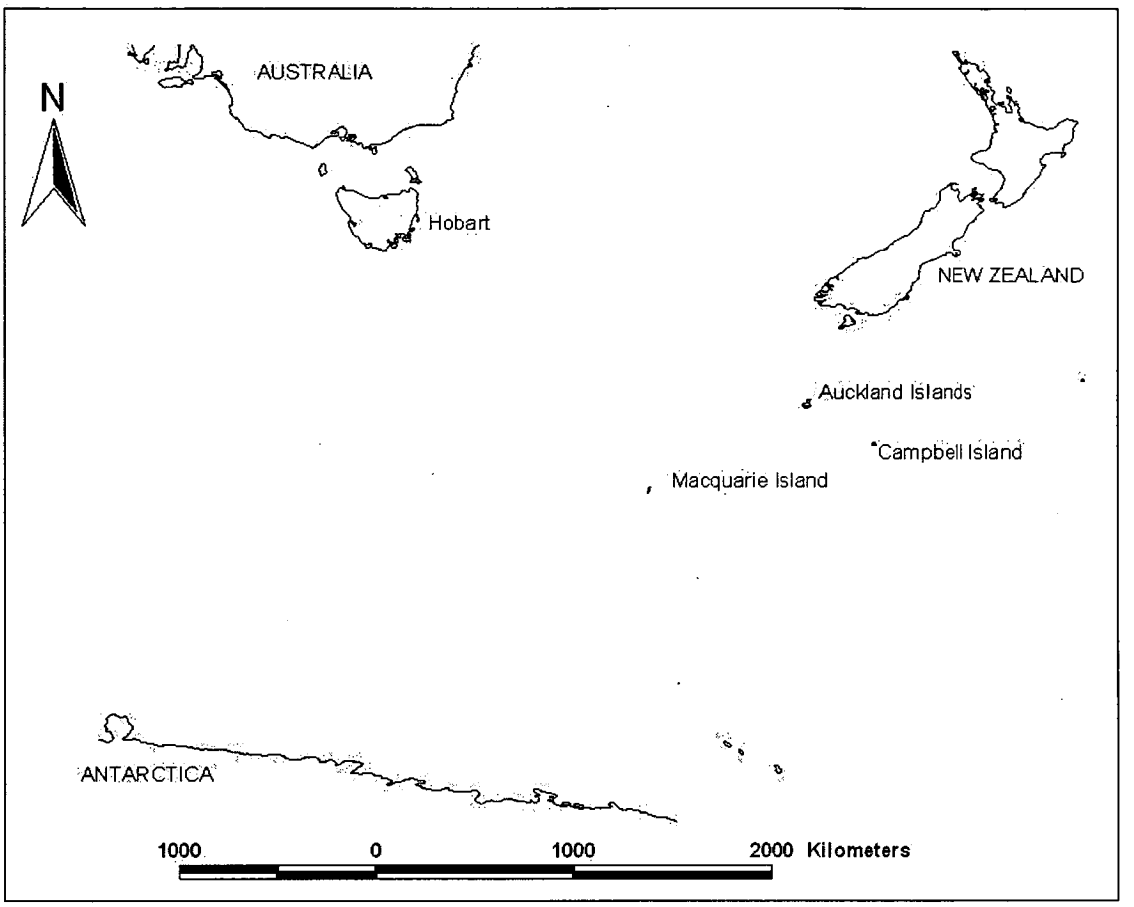

Figure 4.1: Location of Macquarie Island which lies approximately 1540km south-east of Tasmania.

Methods

The presence of a biosecurity hazard in the form of a barge heavily fouled with marine biota was noted during an investigation of potential pathways and vector platforms for non-indigenous biota associated with an Australian Antarctic Program expedition to Macquarie Island (54°30'S, 158°57'E) (Whinam *et al.* 2005). Table 4.1 shows the history of the barge which was exposed to settlement by marine biota in the Derwent River (Hobart, Tasmania) for longer than one month prior to loading aboard the research and supply vessel *RSV Aurora Australis* on Voyage 8 bound for Macquarie Island. The barge was intended to be used to retrieve heavy equipment from the shore to the supply vessel.

Table 4.1: The time sequence of the barge intended for deployment at Macquarie Island. Information was extracted from the situation reports of the RV Aurora Australis.

Date	Activity	Temp	Time of Emersion (hrs)
23-26.01.2002	Barge introduced to the Derwent River	-	-
09.03.2002	Barge loaded: ~ 17:00h		0
10.03.2002	V8 Departs: 1705h		24.05
11.03.2002	Barge inspected: 900h	12.5	40
	Barge Steam-cleaned: 1600h		47
12.03.2002	Voyage report: 1600h	11.4	71
13.03.2002	V8 Arrives at Macquarie Island: 0730h	7.9	*85.30 (theoretical)*

Collection:

The barge was inspected on Monday 11th March, 2002. Following the identification of the barge as a hazard all accessible surfaces were scraped of encrusting biota. The material collected from the barge was immediately frozen and retained for identification and enumeration. As investigators could not reach further than 60cm under the barge, a portion of the underside could not be cleaned. At 4:00 pm on the same day, the barge was exposed to a steam spray to further reduce the hazard and a management decision was made not to deploy the barge at Macquarie Island.

Identification:

The material collected from the barge was floated in fresh water, homogezied and separated into thirds (33.3%). Each third was divided into quarters (8.3%) and again into quarters (2.1%). Half (1.05%) of two 2.1% sub-samples was retained from each third to provide a total of six ~1% sub-samples. Each sub-sample was fractioned into three classes: 0.5mm, 1mm and 2mm. Samples were identified using a dissecting microscope and dominant species were counted in a Bogorov sorting tray to provide an extrapolation of the total population associated with the barge.

Hazard Assessment:

A basic hazard assessment was conducted according to the protocol set out in Hays and Hewitt (2000a). This approach compares the thermal similarity between donor and recipient regions and

uses this similarity as a proxy for the hazard of biological transfer between regions. The Gower Similarity Coefficient (Gower 1971) was used to gain a similarity measure based upon the maximum and minimum water temperatures from each month (see Hayes & Hewitt 2000a for a review of this approach). The similarity coefficient compares a characteristic 'k' (monthly thermal extremes) of two entities i and j, and allocates a score s_{ijk} which is zero when i and j are non-overlapping different, a positive fraction when there is some degree of similarity, and unity when i and j are identical (Hayes and Hewitt 2000a). For the purpose of this assessment a similarity measure of >0.5 is considered significant. This approach calculates the similarity as follows:

$$S_{ij} = \sum_{k=1}^{n} s_{ijk} / \sum_{k=1}^{n} \delta_{ijk}$$

Where $\delta_{ijk} = 1$ when character k can be compared for i and j, and zero when it cannot due to missing data.

Results

At the time of initial inspection of the barge, it had been out of the water for at least 40 h (Table 1). Three species of green algae and one species of red algae formed a substantial habitat matrix upon the sides and hull of the barge. Within this algal habitat the presence of numerous live crustaceans (amphipods and crabs), starfish (*Pateriella regularis*), and mussels (*Mytilus galloprovincialis*) were observed. Underneath the barge an extensive surface encrusted by barnacles (*Elminius modestus*) was estimated to include millions of individuals. Many of the barnacles were dead, or showed signs of severe dehydration.

Table 4.2 shows the species identified from samples collected from the Macquarie Island barge. Of the 20 species recorded, eight species are considered as introduced to Australia, and a further two species that are native to Australia have established invasive populations in other regions. Many ovigerous individuals of the brooding amphipods *Caprella acanthopgaster, Monocorophium acherusicum* and *Jassa marmorata* were sampled. Likewise, mature ovicells were present on the bryozoan *Tricellaria occidentalis* and gonotheca were present upon the hydroid *Obelia dichotoma.*

Table 4.2: Species identified from the fouling community attached to the barge. Species that are known to be introduced to Australian waters are marked (*) and species that are native to Australia but non-indigenous elsewhere in the world are marked (§). References documenting the invasion history of the species are provided.

Taxon Group	Species	Native distribution	Refs
Algae	*Ulva rigida* (Sea lettuce)	Cosmopolitan	
	Enteromorpha intestinalis (Green algae)	Cosmopolitan	
	Cladophorpha sp. (Green algae)	N/A	
	Rodophyta sp. (Reg algae)	N/A	
Crustacea	*Elminius modestus* § (Barnacle)	Australia (introduced to UK)	Crisp (1958)
	Zeuxo sp (tanaid)	N/A	
	Petrolisthes elongatus * (NZ half-crab)	New Zealand	Aquenal (2002)
	Jassa marmorata * (amphipod)	Atlantic, Nth Pacific	Poore & Storey (1999)
	Monocorophium acherusicum * (amphipod)	Europe	Poore & Storey (1999)
	Caprella acanthogaster * (amphipod)	N Hemisphere	Guerra-Garcia & Takeuc (2004)
	Caprella penantis (amphipod)	Cosmopolitan	
	Paridotea ungulate (isopod)	Cosmopolitan, NZ sub-Antarctic Is.	
	Fa, Sphaeromatidae (isopod)	N/A	
Bryozoa	*Watersiporia subtorquata* * (Encrusting bryozoan)	Nth Hemisphere (introduced to Aust., NZ)	Keough and Ross (1999)
	Tricellaria occidentalis * (Erect bryozoan)	Nth Hemisphere (introduced to Aust., NZ)	Keough and Ross (1999)
Hydroids	*Obelia dichotoma* * (Hydroid)	Cosmopolitan (introduced to Aust.)	Watson (1999)
Ascidian	*Asterocarpa humilis* (Ascidian)	Sth Hemisphere, East Pacific	
Mollusca	*Mytilus galloprovincialis* § (Mussel)	Cosmopolitan (introduced to South Africa)	Stewart Grant & Cherry (1985)
Echinodermata	*Pateriella regularis* * (Cushion star)	New Zealand	Aquenal (2002)
Insecta	Fa. Chironomidae (Midge larvae)	N/A	

Due to the fractured state of sessile organisms such as hydroids and barnacles, reliable quantification of populations was restricted to mobile organisms. Three species of amphipod known to be non-indigenous in Australian waters were counted in each of the sub-samples (Table 4.3). Extrapolations estimating the number of individuals collected from the 60cm band scraped from the barge yielded a population estimate of 136 000 individuals for *Monocorophium acherusicum*, 3 270 individuals of *Jassa marmorata* and 3 910 individuals of *Caprella acanthogaster*.

Table 4.3: The numbers of three species of non-indigenous amphipod recorded in the sub-samples taken from the barge census. Numbers of individuals recorded in each sub-sample (n), the mean number of individuals (x) and the estimated total population of the barge (N) are provided for each size-based fraction.

		Monocorophium acherusicum		*Jassa marmorata*		*Caprella acanthogaster*	
		n	***x***	***n***	***x***	***n***	***x***
500 µm fraction	1	387	418.3	1	0.5	3	2.8
	2	419		0		4	
	3	471		0		1	
	4	407		0		6	
	5	423		0		2	
	6	403		2		1	
1mm fraction	1	578	598.7	8	4.2	3	8
	2	619		2		8	
	3	605		4		6	
	4	623		3		10	
	5	591		5		9	
	6	576		3		12	
2mm fraction	1	350	349	28	28	26	28.3
	2	357		22		31	
	3	294		34		23	
	4	347		27		21	
	5	398		30		37	
	6	348		27		32	
N		**136600**		**3270**		**3910**	

Discussion

Our findings highlight an important and often overlooked component of Southern Ocean quarantine procedures. Clearly, any object immersed in the marine environment for a significant period will accumulate a community of sessile epibenthic invertebrates which can provide a habitat matrix for various motile organisms. The fouling community recorded on the barge colonised and established over a one month period in a temperate estuarine system. Included in this assemblage were several invasive species that have displaced native species, including some endemics, in temperate waters. The question of wether it would it have been possible for the species from the barge to establish in a sub-Antarctic coastal environment is explored below.

The biological, chemical and physical environment of a recipient region will directly affect the ability of an introduced organism to establish a population in the new habitat. Although attempts to predict the invasiveness of organisms based upon such attributes have generally provided only marginally useful information, a few key traits have been used to predict the potential for a species to survive the process of uptake, transport and establishment associated with human-mediated marine introductions (Hays and Hewitt 2000a). Prolonged emersion of the barge would have been a key parameter affecting survival during the four-day transit time. Sea temperature would have also effected survival in the event that live organisms were introduced to the littoral Macquarie Island environment.

Emersion response

Species able to survive in intertidal habitats are more likely than subtidal speciues to survive prolonged periods of emersion due the periodic exposure to the atmosphere associated with their habitat (Coleman 1973; Kennedy 1976; Davenport and Irwin 2003; Greenaway 2003). Littoral mussels capable of retaining fluids within their mantle cavity to prevent desiccation can survive for days out of the marine environment, and *Mytilus edulis* has been shown capable of surviving emersion for periods as long as 200 hours (Kennedy, 1976). It seems likely that the *Mytilus galloprovincialis* observed on the barge would have been able to survive the ~85hr journey to Macquarie Island.

Barnacles are particularly well adapted to survive emersion due to their ability to undertake aerobic respiration whilst guarding against desiccation through the opening and closing of their valves (Barnes and Barnes, 1957; Barnes *et al.*, 1963; Davenport and Irwin, 2003). For example, the inter-tidal species *Jehlius cirratus* can survive emersion (LP100) for up 75days (LP50 = 25days) (Castro *et al.*, 2001). While no experimental data for *Elminius modestus* was found to demonstrate comparable lethal periods of exposure, this species has been shown to survive prolonged periods (>20 hrs) in circumstances where the mantle cavity is entirely filled by air (Davenport and Irwin 2003).

The observation of live New Zealand porcelain crabs (*Petrolisthes elongatus)* amidst the fouling demonstrates that the environmental conditions within the matrix of macrophyte fouling can

provide micro-environments capable of supporting species sensitive to desiccation. Jones and Greenwood (1982) showed that *P. elongatus* was vulnerable to dehydration during emersion, and demonstrated that a lethal body-water loss of 20.8% would occur in large crabs within 26 h of exposure, and that lethal exposure periods were shorter in smaller individuals. The observation of live crabs capable of unimpaired movement on the barge after 40 h of emersion would indicate that the humid micro-environments within the dense canopy of *Ulva rigida* are capable of providing refugia to more vulnerable species. Such micro-habitats have previously been shown to support sensitive assemblages during trials of emersion as a control measure for NIS (Garnham 1998; McEnnulty *et al.* 2001). The barge was secured to the front deck of the Aurora Australis and would have been exposed to humid sea air as well as wave splash, factors which may have contributed to the maintenance of an amenable micro-environment during transport.

While the exposure to the atmosphere for a period of 84 h clearly represents a stress to individuals entrained upon the barge, such a stress may trigger spawning or the release of propagules and thus increase the potential for a release of individuals into sub-Antarctic environments. The barnacle *Elminius modestus* has been shown to respond to periods of prolonged emersion by closing the opercular valve and storing larvae which are released in large quantities upon re-immersion (Cawthorne and Davenport 1980). Likewise, stress often induces spawning in mytilid mussels. Stress-induced larval release by *Mytilus galloprovincials* has been observed to enable liberated larvae to successfully settle on surfaces even in environments that are clearly causing stress in the mature individuals (Apte *et al.* 2000).

Thermal similarity

The thermal similarities of two regions have previously been employed as a measure of risk for marine introductions through an environment-matching approach (Hilliard and Raaymakers 1997). A comparison of the thermal regime of the Bruny bioregion (southern Tasmania) (the donor environment) and Macquarie Island (the recipient environment) is provided in Fig 4.2b. A simple hazard assessment (following Hayes and Hewitt, 2000a) was used to determine the potential for species from the Hobart biogeographic region to survive transfer to Macquarie Island. Figure 4.2a shows the result of the hazard assessment and indicates a considerable similarity (>0.5) between the regions for eight months of the year (April to November). The four

summer months when similarities between Tasmanian and Macquarie Island are below 0.5 (including March when the barge was destined for the island), however, may be sufficient to prevent the establishment of temperate species, particularly when this period coincides with the peak reproductive period of potentially invasive organisms.

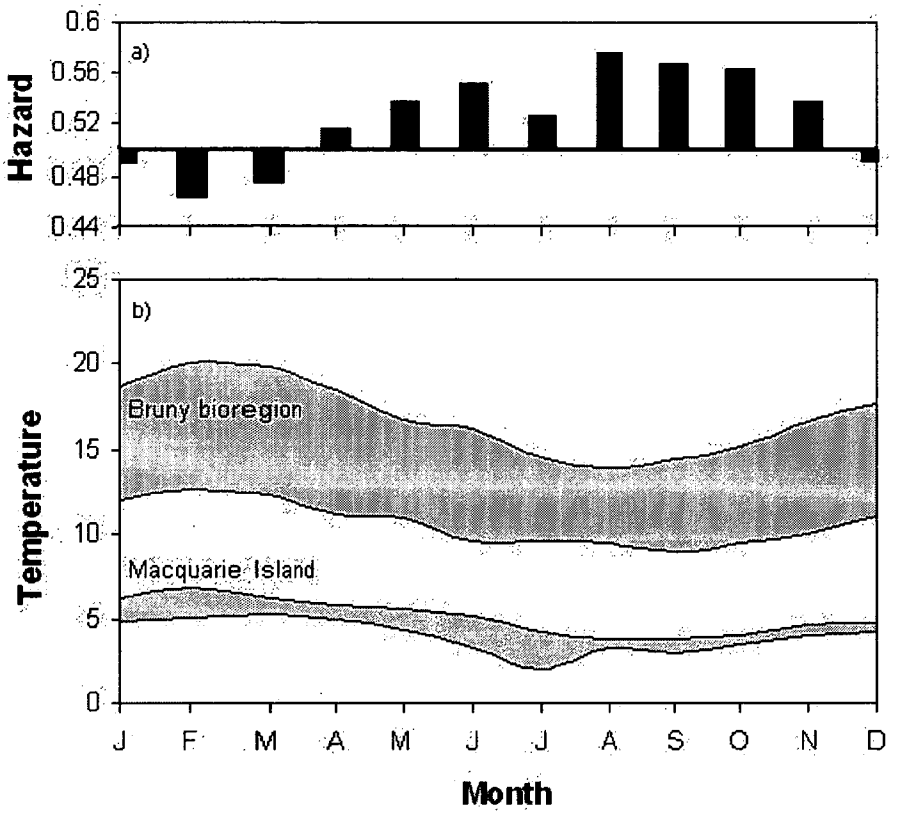

Figure 4.2: **(a)** Hazard assessment based upon the thermal similarity of the Bruny bio-regions Tasmania and Macquarie Island. The hazard rating was calculated using the Gower Similarity coefficient (Gower, 1971) based upon the monthly maximum and minimum temperatures. **(b)** Thermal ranges of the Bruny Bioregion and Macquarie Island. Bruny thermal data was provided by the Centre for Research on Marine Introduced Species (CRIMP). Macquarie Island thermal data was provided by the National Tidal Facility (NTF).

The results of the hazard assessment should be treated with some degree of caution and the use of thermal comparisons to denote bio-security hazards have been criticised because most species have thermal tolerances that extend well beyond the extremes recorded in their environment (Hewitt and Hays 2002). Species-specific risk assessments are generally advocated as a more conservative approach (Hays and Hewitt 1998; 2000a; 2000b; Hewitt and Hays 2002). Little data is available regarding the thermal tolerance of the species recorded in this study. An examination

of some well known invasive species however, indicates that several invasive organisms established in Tasmanian coastal waters are capable of surviving in the temperatures typical of Macquarie Island (Figure 4.3). Despite no overlap occurring in the thermal regime of the two environments (Figure 4.2) it is clear that many invasive species are able to survive in both regions and it is plausible that other species such as those entrained upon the barge could also establish in the coastal waters of Macquarie Island.

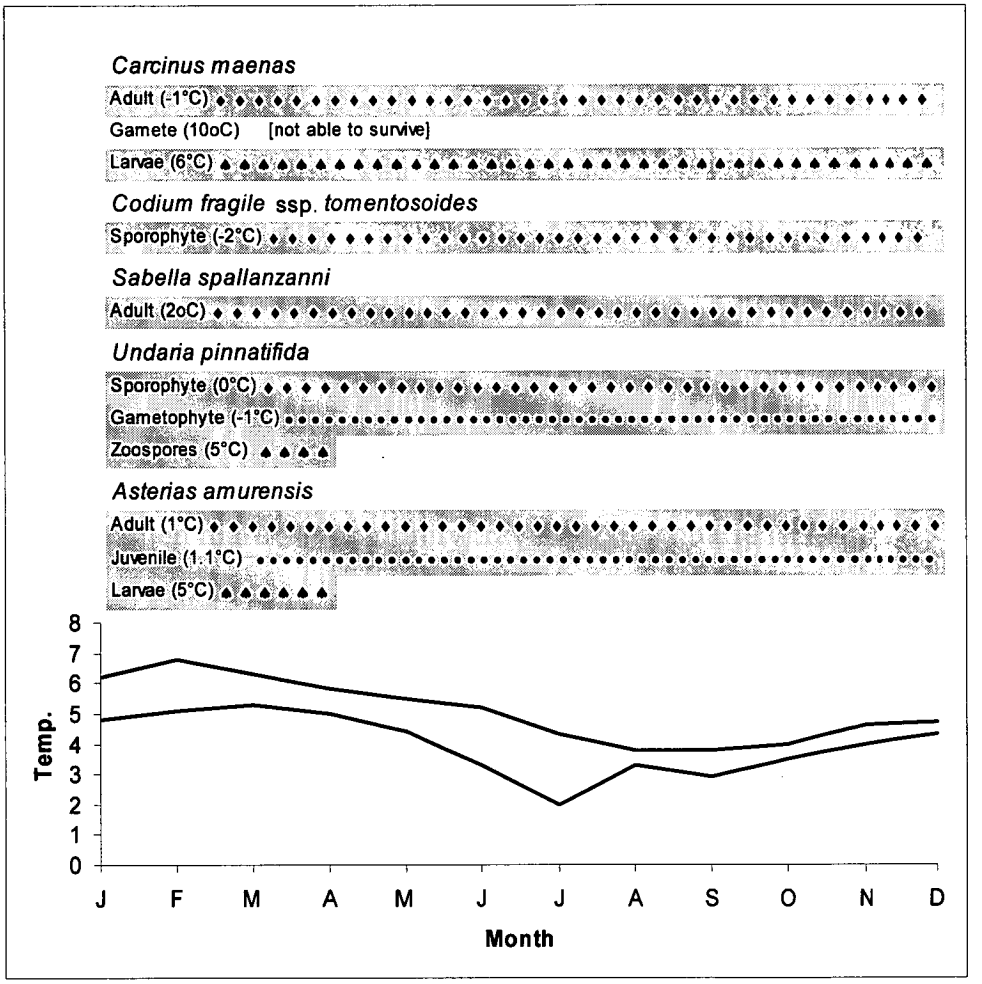

Figure 4.3: The lower thermal tolerances of five species of invasive marine pests established in Tasmanian coastal waters compared with the thermal range of Macquarie Island coastal waters. Lower thermal tolerances are provided in parenthesis, and the ability to survive in Macquarie Island is demonstrated by the band of symbols corresponding to survival during each month. While larval tolerances of *Carcinus maenas* precludes this species from establishing in Macquarie Island, other species are able to complete their life-cycle and are considered as high-risk species. Thermal tolerance data was provided by the Centre for Research on Introduced Marine Pests (CRIMP). Thermal data was provided by the National Tidal Facility (NTF).

Concluding remarks

The observation of a viable marine assemblage entrained on an object intended for deployment at Macquarie Island highlights just one of the many mechanisms by which non-indigenous marine organisms can be introduced to the sub-Antarctic islands. Since the recognition of the pathway, the Australian Antarctic Division has introduced barge cleaning procedures consisting of obligatory emersion periods and high-pressure cleaning prior to loading of marine equipment, with particular attention paid to the cleaning of water inlets and immersed surfaces. The Australian Antarctic Division adaptive management strategy has also incorporated an awareness of biosecurity in the quarantine education program for expeditioners. Such education of expeditioners and logistics officers and the introduction of formal guidelines can reduce the biosecurity hazard associated with material that may be immersed in marine and freshwater environments in the sub-Antarctic.

Acknowledgements

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Section II

Phylogenetics

Chapter 5: Conservation of Genetic Diversity

The unique genetic identity of sub-Antarctic *Mytilus* populations: a case for the conservation of discreet genetic units

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Abstract

The blue mussel, *Mytilus galloprovincialis*, is a natural component of the inshore fauna of both hemispheres. This species is frequently observed within fouling communities on vessel hulls and has also been transported across the globe for the purpose of mariculture. As a result hybridisation is frequently observed between populations and also between species in the *Mytilus* complex. Non-indigenous *Mytilus* populations introduced to regions where they do not naturally occur have been reported as causing significant ecological damage. This study examines populations of *M. galloprovincialis* in the Southern Hemisphere to determine the extent of hybridisation between natural populations that occur in the region and cosmopolitan populations sourced from the Northern Hemisphere. Populations in busy ports regions subjected to a high level of shipping activity host populations of *M. galloprovincialis* that share a high affinity to Northern Hemisphere stock. Conversely, remote populations such as those collected from the New Zealand sub-Antarctic islands hold a unique genetic structure that is distinct from the cosmopolitan *Mytilus*. In a species complex with a genetic structure markedly homogenised by anthropogenic connectivity between populations, remote Southern Hemisphere populations represent important examples of genetic diversity. The conservation of the genetic integrity of isolated populations is an important issue that is often overlooked.

Introduction

Mussels from the *Mytilus* species complex form an important component of the shallow benthic marine community of both Hemispheres. Global surveys of allozyme variation have clearly delineated three species within this complex - *Mytilus. edulis, M. galloprovincialis* and *M. trossulus* (McDonald & Koehn, 1988; Varvio *et al.*, 1988; Kohen, 1991; McDonald *et al.*, 1991). *Mytilus* from the Australasian region have generally been recognized as belonging to *M. galloprovincialis* (McDonald *et al.*, 1991). It has been noted that populations from this region possess a unique genetic structure relative to populations from the Northern Hemisphere, and these populations may deserve to be considered as a subspecies of *M. galloprovincialis* (Daguin & Borsa, 2000).

Although *M. galloprovincialis* is clearly a native component of the Australasian marine ecosystem, this species is frequently observed within fouling communities on vessel hulls and has also been transported across the globe for the purpose of mariculture. These anthropogenic transport mechanisms have resulted in the establishment of non-indigenous populations of this species in some Southern Hemisphere locations where the species does not naturally occur (e.g., Chile – Daguin & Borsa, 2000; South Africa – Stuart-Grant & Cherry, 1985). Populations introduced to South Africa have proven to be highly invasive, substantially modifying the coastal ecosystem by displacing native species and causing a dramatic increase in intertidal biomass (Robinson *et al.*, 2005).

Daguin & Borsa (2000) indicate that *M. galloprovincialis* populations from the Australasian region have not experienced substantial introgression by alien gene lines, however it has been suggested that some genes within this stock hold *M. edulis* affinities that may originate from hybridization with this species which is reportedly present in the sub-Antarctic Kerguelen Islands and the Falkland Islands (McDonald, 1991). Mitochondrial DNA evidence provided by Hilbish *et al.*, (2000) further clarifies the nature of the two distinct lines of *M. galloprovincialis* within the Australasian region and suggests that there have been two introductions of *Mytilus* spp. from the Northern Hemisphere to the Southern Hemisphere. Most mtDNA lineages relate to an ancient migration event occurring in the Pleistocene, however a few lineages trace their origin to a second and more recent migration through the Atlantic Ocean (Hilbish *et al*, 2000).

Most genetic studies of *M. galloprovincialis* in the Australasian region have focused upon broad trends in Southern Hemisphere populations. Few researchers have examined regional population differences or the distribution of the two lineages of Mussels described by Hilbish *et al* (2000). Morphometric studies of *Mytilus spp.* carried out by Gardner (2004) suggested two morphologically distinct populations within New Zealand. *M. galloprovincialis* type mussels were shown to be widespread, extending to the sub-Antarctic islands, while *M. edulis* type mussels were restricted to the Bay of Islands in Northern New Zealand. It was also surmised from an analysis of historical midden contents that native stock in the region was derived of *M. galloprovincialis* type mussels whilst the *M. edulis* type stock may represent a more recent introduction (Gardner, 2004).

The anthropogenic introduction of Mytilid mussels from the Northern Hemisphere into the Southern Hemisphere has two implications for native communities. Foremost, ecosystems which are naturally devoid of mussels can experience rapid changes in littoral communities and the displacement of native species as has occurred in South Africa. A second more subtle impact may arise from the hybridization of natural *Mytilus* stock and the erosion of the genetic diversity which is unique to the Southern Hemisphere stock of *Mytilus galloprovincialis*. Whilst the first impact may be identified through monitoring, difficulties arise in distinguishing whether the introduction is indeed mediated by human mechanisms or whether it represents a natural range expansion through natural dispersal. The hybridization of Austral *M. galloprovincialis* with alien gene lines is even more difficult to monitor.

This study has been prompted by a growing concern over the threat of marine introductions to Australia's remote high latitude coastlines, and particularly the possibility that *M. galloprovincialis* may, in the future, be introduced to the sub-Antarctic Macquarie Island. Although few species have been recorded as introduced to high latitude coastlines, observations of non-indigenous spider crabs (Tavares & de Melo, 2005) and algae (Clayton *et al.*, 1997) in the Antarctic Peninsula, and observations of several introduced invertebrates to the New Zealand sub-Antarctic islands (Cranfield *et al.*, 1998) demonstrate that this region is not immune to introductions.

No populations of *Mytilus spp.* are presently considered as introduced to the Southern Ocean islands, yet a single specimen of a mytilid mussel identified as *M. edulis* was reported from South Georgia Island where it was believed to have been introduced (Ralph *et al.*, 1976).The native range and environmental tolerances of *M. galloprovincialis* predicts that the remote Macquarie Island should be within this species thermal tolerance range although it has not presently been recorded from the island. The species is frequently observed in hull fouling communities on vessels traveling to this island (Lewis *et al.*, 2003, 2005) and specimens collected from the temperate port of Hobart have been shown to be capable of surviving and spawning in water temperatures replicating Macquarie Island and even Antarctic thermal conditions (see Chapter 6).

Despite the absence of mussels at Macquarie Island, *Mytilus galloprovincialis* is a conspicuous component of the littoral fauna of the New Zealand sub-Antarctic islands. This study aims to examine the genetic structure of mussel populations from the Auckland and Campbell Islands to determine their relatedness to populations from Australia and New Zealand and to examine the distribution of the native lineage designated as sub-specific to Northern Hemisphere stock by Daguin & Borsa (2000). The distribution of additional lineages of *M. galloprovincialis* will be examined from the perspective that lines with a high affinity to Northern Hemisphere stock represent modern introduction events. By assessing communities from the New Zealand sub-Antarctic islands the status of these populations as native or introduced will be established. The relation of these populations to port locations will further clarify the providence of these populations.

Methods

Sample Collection:

Mytilus galloprovincialis were collected from Australia, New Zealand, the Auckland Islands, Campbell Island and South Africa (see Figure 5.1). At each site 20 individual specimens were collected by hand from a shoreline area no greater than 20m. Individuals had their adductor muscles cut to ensure correct preservation and were stored in 80% ethanol. The specimens were

carefully examined for diagnostic morphological features that confirmed their identity as *M. galloprovincialis.*

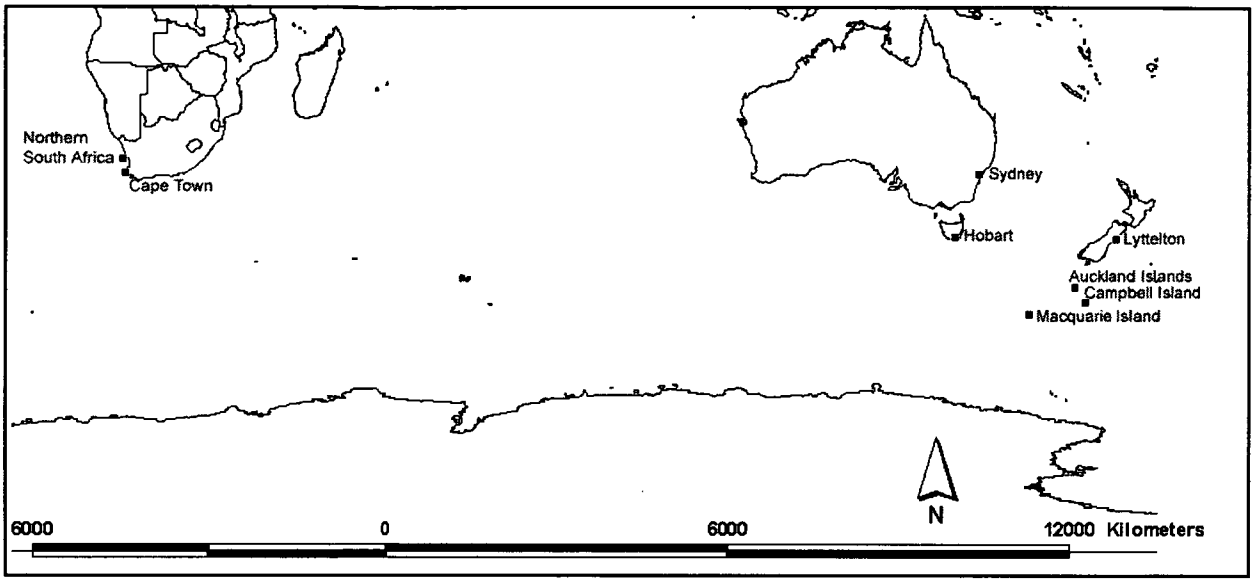

Figure 5.1: Sample locations for *Mytilus galloprovincialis* collected in the current study. NB. The position of Northern South Africa is adjacent to the coastal town of Saldanha.

Production of Mitochondrial DNA sequences

Adductor muscles were dissected from each individual and the extraction of genetic material was made using a DNA Tissue Extraction Kit according to the manufacturers' protocol (Mo Bio). Care was taken to ensure that no gonad material was included in extraction samples to minimize the potential for incorporating male-inherited mtDNA into the analysis. An ~690 base pair region of the mitochondrial COI region was amplified through polymerase chain reaction (PCR) using the "universal" primers HCO (5'-taaacttcagggtgaccaaaaaatca-3') and LCO (5'-ggtcaacaaatcataaagatattgg-3') (Folmer *et al.*, 1994).

Each 100μL PCR contained ~100ng purified *M. galloprovincialis* DNA from one individual mussel. The reaction buffer contained 50 mM KCl, 10mM Tris-HCl pH 8.9, 0.1% Triton X-100 15 mM MgCl2, 1μM of each primer, 2 mM of each dNTP and 2 units *Taq* DNA polymerase (Sigma). The reactions had an initial incubation at 94°C for 2min to denature template DNA, followed by

thermal cycling at 94ºC for 5 s, 43ºC for 1min and 72ºC for 1 min. This was repeated for 40 cycles. A 6min incubation at 72ºC followed to finish synthesis of incomplete strands.

PCR products were purified using an 'Ultra-Clean' PCR product purification kit (MoBio). The concentration of purified PCR products was measured with PicoGreen fluorescence in a Turner Designs PicoFlour microflourometer. 5 ng PCR product was used as a template for 20μL Big Dye Terminator (ABI) sequencing reactions. These were analysed on an ABI Prism 377xl automated DNA sequencer at the Australian Genome Research Facility.

DNA Sequence Data Analysis:

The COI sequence electropherograms were manually corrected using Chromas® Version 1.45 software. The sequences were submitted to GenBank and given accession numbers DQ864378-DQ864433. Additional mytilid Mitochondrial COI sequences were taken from Genbank (accession codes: AY723898.1, AY130055.1, AY723899.1, AY130058.1, AF242017.1, AF242014.1, AF527535.1, AF242021.1, AY130021.1) and incorporated into the analysis to provide data from populations in Northern Hemisphere locations. Sequence data from male-inherited mtDNA was incorporated into the data set to ensure that differences within the study populations were obtained using female rather than male-inherited ntDNA.

Sequences were aligned using ClustalX® Version 1.81 (Thompson *et al.*, 1997) Phylogenies were estimated using Molecular Evolution Genetic Analysis (MEGA) version 3.0. Phylogenies were constructed using Maximum Parsimony (Nei & Kumar, 2000) and Minimum Evolution (Rzhetsky & Nei, 1993) methods employing a Tamura-Nei (1993) substitution model. Bootstrap estimates of confidence in nodes were calculated with 1000 pseudoreplicate datasets.

Calculation of genetic and geographic distances

A matrix comparing the mean Tamura-Nei genetic distance between locations examined in this study and locations of GenBank material was created using the arithmetic mean of all pairwise genetic distances between individuals from each location. The genetic distance separating populations from each location was plotted against the great circle distance between the two

geographic locations. Great circle distances were used to provide the most accurate assessment of geographical separation between the populations. For coastal populations separated by landmasses, distance was estimated using waypoints that skirted the coastline, ensuring that the great-circle distance represented an accurate assessment of the separation between populations.

Comparisons of genetic distances in Australasian Mytilus and trans-Panamanian Arciidae

The Tamura-Nei genetic distance between all unique COI alleles recorded from *Mytilus* in Hobart and all unique alleles recorded from *Mytilus* in the Auckland and Campbell islands was calculated. The Tamura-Nei genetic distance between unique COI alleles from 'germinate' species pairs found on either side of the isthmus of Panama as identified by Marko (2002) was also calculated. These COI regions are orthologous. A comparison of the genetic distance between theses species and *M. galloprovincialis* enables a rough estimate of the time at which *Mytilus* populations diverged.

Results

All mitochondrial COI sequences from *Mytilus galloprovincialis* populations analysed in this study were clearly derived from female inherited mitochondrial lines. This was checked by aligning the sequences with DNA from a male derived mitochondrial COI sequence (GenBank accession code AY363687.1) and constructing a phylogeny from this dataset. All of the COI sequences from individuals collected in this study and from maternal-derived COI data taken from GenBank formed a cohesive group. Male-derived sequences formed a distinct and very distant out-group with a Tamura-Nei genetic distances from other sequences consistently greater than 0.2.

A phylogenetic tree incorporating all data included in the current study is provided in Figure 5.2. The tree was calculated using minimum evolution clustering incorporating the Tamura-Nei model. Populations of *M. galloprovincialis* from the sub-Antarctic Auckland and Campbell Islands form a separate clade which also includes populations collected from Hobart. This "Austral clade" forms a distinct group supported by 94% of pseudoreplicate datasets from the rest of the *Mytilus* species complex that includes *Mytilus galloprovincialis, Mytilus edulis* and *Mytilus trossulus.*

Within this group, individuals from Hobart form a distinct sub-group with 99% bootstrap support, and individuals from the Auckland and Campbell Islands fall within two subgroups which each sharing individuals from both islands.

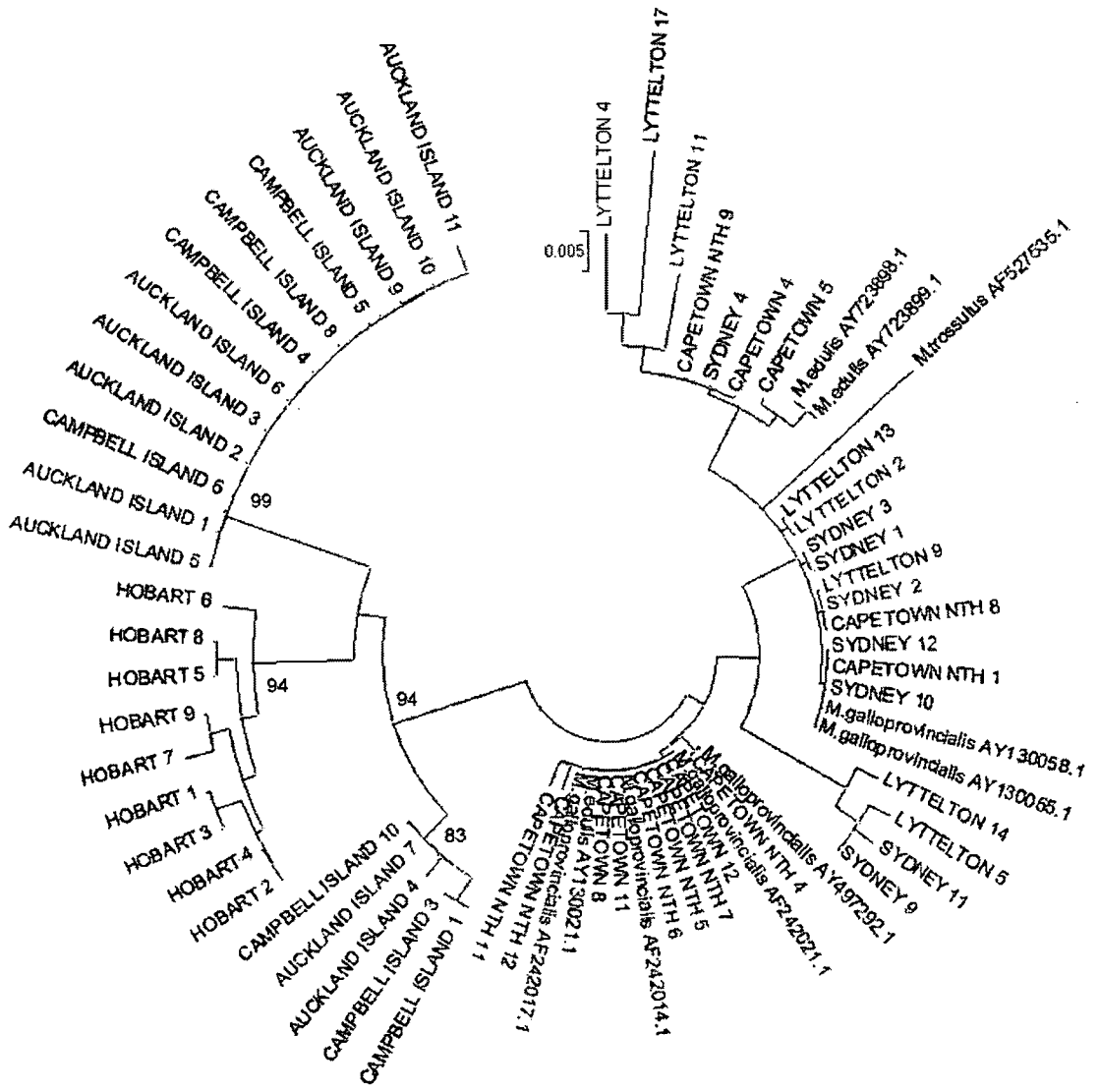

Figure 5.2: Minimum Evolution phylogeny estimated with the Tamura-Nei model of DNA evolution. Values indicate percentage bootstrap support for nodes calculated with 1000 replicates. Specimens extracted from genbank are included with accession codes.

It is of note that populations of *M. galloprovincialis* collected within busy port environments of Australia (Sydney) and New Zealand (Lyttelton) do not group within the Austral clade but fall within the broader species complex characterised by Northern Hemisphere populations of *Mytilus*. Similarly, individuals collected from the introduced population of *M. galloprovincialis* in South Africa group within this cosmopolitan *Mytilus* complex. Populations from South Africa (Cape Town, and Cape Town North) and populations from large Australian and New Zealand ports (Sydney and Lyttelton) do not form distinct clades within the *Mytilus* species complex and individuals shared an affinity to various Northern Hemisphere individuals of all species within the complex.

Comparison of genetic and geographic distances

A comparison of genetic distance and the geographical distance separating populations serves to further elucidate the distinct structure of sub-Antarctic populations relative to cosmopolitan populations in the Southern Hemisphere (Figure 5.3). Population comparisons all show a similar, positive, relationship between geographical distance and genetic distance. Nethertheless, while comparisons between Northern Hemisphere populations (indicated by ×) reveal relatively low levels of genetic distance, comparisons of "Austral" populations from the Southern Hemisphere with cosmopolitan populations (indicated by ○) demonstrate consistently higher genetic divergence at similar geographical distances.

Notably, the genetic distances between "Austral" populations and populations sourced from nearby ports, as well as introduced populations from South Africa, ("local cosmopolitan" populations indicated by Δ) are amongst the highest recorded despite their geographical proximity. Austral mussels from busy port environments and those collected from more remote locations and the sub-Antarctic islands posses a genetic distance far in excess of that predicted from their geographic separation.

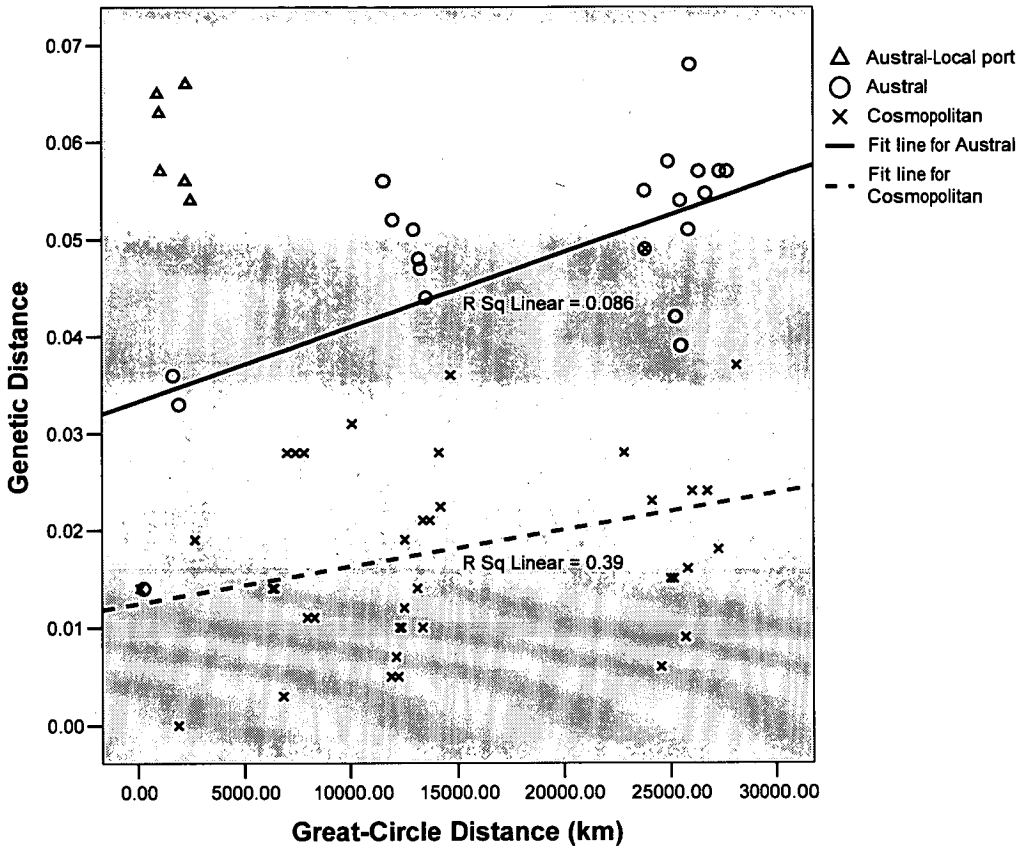

Figure 5.3: Comparison of genetic distance between populations and the Great-circle distance separating the populations.

Comparisons of genetic distances in Australasian *Mytilus* and trans-Panamanian Arciidae

The mean Tamura-Nei genetic distances calculated from several comparisons of *Mytilus* and Arciidae COI haplotypes are shown in Table 5.1 below.

Table 5.1: Mean genetic distance between populations of *Mytilus* from Hobart and the sub-Antarctic islands compared to distances between species of Arciidae published by (Marco, 2002).

Comparison	N comparisons	Mean Tamura-Nei genetic distance
Hobart *Mytilus* – subAntarctic *Mytilus*	36	0.0326
Barbiata illota – Barbiata tenera	8	0.1565
Barbiata candida– Barbiata reeveana	9	0.1536
Arca mutabilis – Arca imbricata	4	0.3085

Discussion

Mytilus galloprovincialis is currently considered to be a native component of the Southern Hemisphere marine fauna that dispersed naturally from the Northern Hemisphere during the Pleistocene (Hilbish *et al.*, 2000; Gardner, 2004). In addition to this native component of the mytilid fauna, humans have recently introduced additional populations of *M. galloprovincialis* to various locations including South Africa (Stuart-Grant & Cherry, 1985) and South America (Daguin & Borsa, 2000). Such introduced populations are capable of exhibiting invasive characteristics and substantially modifying native assemblages (Robinson *et al.*, 2005).

The object of this investigation was to examine the Austral distribution of *Mytilus* gene-lines with a Northern Hemisphere affinity, and specifically to examine populations of *M. galloprovincialis* in the New Zealand sub-Antarctic islands to explore the hypothesis that they represent artificial introductions to these remote islands. The result of the study clearly delineates two very different maternal mitochondrial lines within Southern Hemisphere populations. The first group includes the introduced population from South Africa and those populations collected from busy Australian (Sydney) and New Zealand (Lyttelton) ports. This clade also includes individuals from Northern Hemisphere studies of all three species within the *Mytilus* complex.

Individuals within this large group display relatively little variation amoung populations and very low levels of genetic differentiation attributable to geographic separation. Comparisons of introduced populations from South Africa, populations from ports in Australian and New Zealand, and populations from the Northern Hemisphere show almost no genetic divergence. Such a pattern is highly indicative that these populations represent anthropogenic introductions to these regions, or at the very least, that a high level of hybridisation between Northern and Southern populations has been facilitated by either commercial translocation of mussel spat, or through the transport of mussels with hull fouling communities. While the former scenario is accepted for populations from South Africa, the presence of natural populations in Australia and New Zealand (Gardner, 2004) suggests that hybridization may have occurred. If this scenario has occurred it would appear that, for the gene region examined in this study, the unique genetic structure of Austral populations sourced from ports has disappeared through homogenisation with Northern hemisphere populations leaving no trace of their Austral providence.

The second clade delineated in the study is strongly differentiated from the cosmopolitan group (90% bootstrap support) and includes populations from the New Zealand sub-Antarctic islands, and also from the port of Hobart. This result strongly opposes the idea that these populations represent modern human introductions. Rather, it appears that despite a broad influx of cosmopolitan genelines in some regions, a distinct Austral stock of *M. galloprovincialis* has persisted in more remote locations. In contrast to the low level of genetic diversity demonstrated in the cosmopolitan clade, the Austral stock shows a relatively high differentiation between the sub-Antarctic islands and the port of Hobart reflecting the natural isolation of these locations. There is also some level of variability within the populations collected from the sub-Antarctic region with two clades that share individuals from both the Auckland Islands and Campbell Island. This variability may relate to stochastic dispersal events associated with natural mechanisms such as kelp rafting which has been shown to be an effective dispersal mechanism for other bivalve molluscs in the region (Helmuth *et al.*, 1994).

The extent to which the austral clade of *M. galloprovincialis* has diverged from cosmopolitan stock is clearly evident when the genetic distance of specimens is compared to the geographical distance that separates populations in the study. Figure 5.4 demonstrates that, in general, these two factors are correlated with an increasing geographic distance serving to isolate populations and enabling divergence to occur. Notably, the populations incorporated in this study clearly segregate into two groups with both groups displaying a similar relationship between geographic and genetic distance. Although the gradient of similarity is directly comparable, austral stock hold a genetic distance that is far greater than that exhibited in the cosmopolitan populations. This comparison of genetic and geographical distance also demonstrates the extent of the difference between natural populations of *M. galloprovincialis,* and populations in nearby ports which hold a strong cosmopolitan affinity. Genetic distance between Austral and local cosmopolitan populations is comparable to those populations with the highest level of geographic separation despite their very close proximity.

One possible explanation for the genetic diversity seen amongst *Mytilus* found at Australasian locations could be a rapid evolution of the COI gene since the mid 17th century when shipping contact between the north Atlantic and Australasia began. The mean Tamura-Nei genetic

distance found between the Australasian *Mytilus* COI haplotypes and the Auckland Islands and Campbell Island haplotypes is 0.033. The 'molecular clock' for *Mytilus* COI evolution cannot be directly calibrated because there are no events at known times that are linked to a subdivision of populations or species of *Mytilus*. However, the mean Tamura-Nei genetic distance in the same COI region in sister species of bivalves from the closely-related family Arciidae separated by the formation of the Isthmus of Panama approximately 5.3-8.5 Mya is 0.184 (Marco, 2002). This comparison suggests that it is highly improbable that the 'Australasian' haplotypes identified here have evolved since ~ 0.0003 Mya) when ships from the north Atlantic first reached Australasia. This very rough measure of genetic divergence among the Australasian clade of *Mytilus* suggests that they have experienced approximately one sixth of the genetic divergence that the trans-Panamanian bivalves experienced, indicating that these *Mytilus* have been in Australasian waters since about 1Mya.

While the Austral stock is clearly distinct from the cosmopolitan populations, the divergence observed in the mitochondrial mtDNA is insufficient to suggest that this stock be considered as a separate species. Figure 5.4 shows the genetic differences observed between populations in this study in relation to differences between several species within the family Mytilidae. While variation between cosmopolitan and Austral stock is of a greater scale than typical of the *Mytilus* species complex it does not approach the degree of genetic separation that typifies species in other genera from the family Mytilidae. While continual hybridization between species within the *Mytilus* complex (Smietanka *et al.*, 2004) has resulted in few species level differences in *Mytilus* species throughout the globe, the historical isolation of Austral populations has allowed them to evolve independently of the meta-population. The resulting divergence between Austral and cosmopolitan stock is far in excess of the variation amoung the three currently recognised species that form this complex.

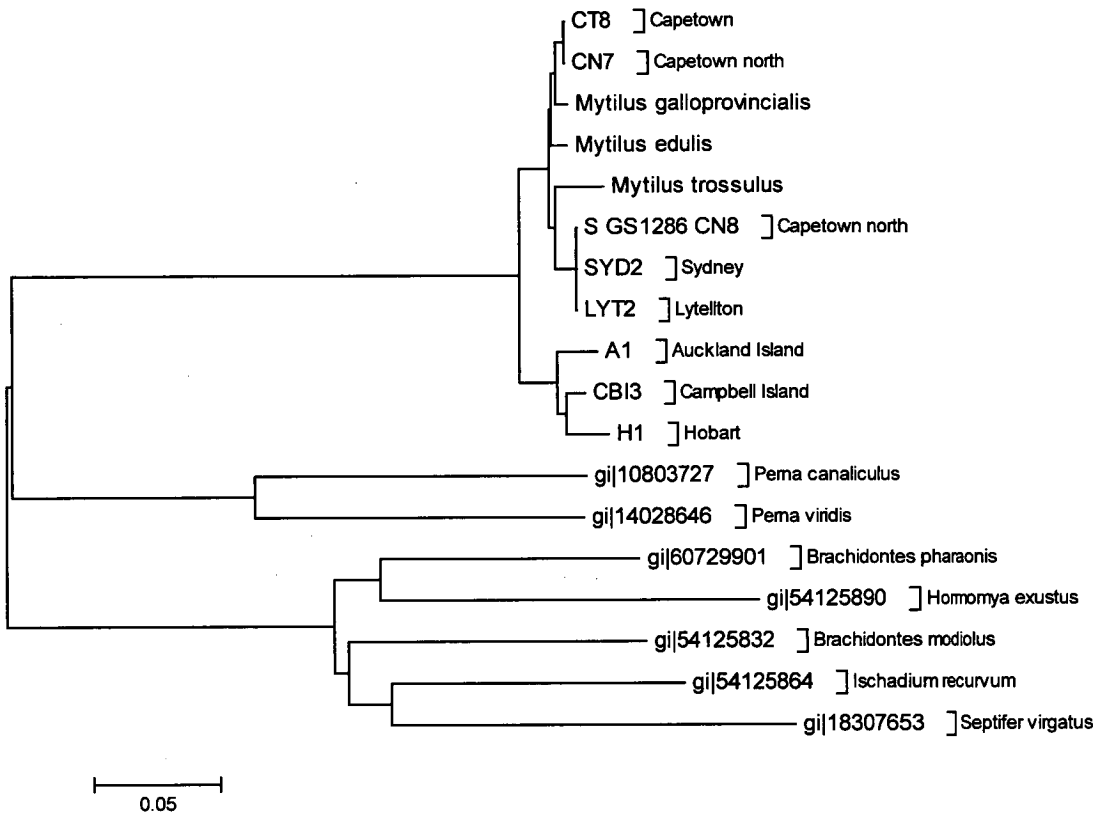

Figure 5.4: Relationship of species and genera within the family Mytilidae as resolved using COI mtDNA sequence data. Data for populations not included in the study was extracted from GenBank.

The incidence of cosmopolitan gene lines within Australian and New Zealand populations of *M. galloprovincialis* is yet another consequence of the erosion of biogeographical boundaries facilitated by the scale of human activities. Over 250 marine species have been introduced to the Australian coastline (Thresher, 1999) however the traffic of organisms is not restricted to those that are naturally absent from these shores. Naturally occurring species with bi-polar or cosmopolitan distributions are also affected by this increase in dispersal opportunity with the predicted result that the genetic diversity of meta-populations throughout the globe will continue to diminish. The rate at which unique genetic characteristics are being eroded by cosmopolitan gene-lines is poorly known and difficult to determine. Although the global loss of diversity may only be detectable through the use of molecular tools, the long-term effects may substantially affect the way in which species adapt to a changing environment.

The homogenization of gene-lines in broadly dispersed species may have significant impacts on the evolution of the species. Given the continual exchange of genetic material facilitated by human transport vectors, isolated populations of *Mytilus* such as those in the New Zealand sub-Antarctic islands represent important reservoirs of genetic information. As large interbreeding populations tend to limit the spread of non-wild-type alleles, the genetic structure of isolated populations may represent important diversity in a population with an unusually homogenous genetic structure facilitated by the human transport of individuals around the world. Invasive species such as Mytilid mussels may be impacting upon their own genetic diversity due to their affinity to human transport methods. The threat to genetic diversity within invasive species is an overlooked component of the general loss of biodiversity associated with the spread of invasive species.

Accelerating rates of species introduction around the globe has been followed by a cavalcade of impacts ranging from local extinctions through to the collapse of entire ecosystems. From a biodiversity perspective, one of the most significant impacts is the extinction of a native species. While terrestrial introductions in the Southern Ocean islands have been directly responsible for extinction events (Frenot, 1996), there tends to be some complacency associated with the threat of marine introductions. Extinction in the marine environment is very rare (Carlton, 1993, Vermeij, 1993, Roberts & Hawkins, 1999, Carlton, 1999) and no extinction event has yet been attributed to a marine introduction.

This resilience to extinction is likely to result from the open nature of aquatic ecosystems and the long distance recruitment of new individuals to coastlines with populations that have been locally depleted. These same phenomena have resulted in many marine species holding wide distribution with only small genetic differences over broad geographic scales (Pulumbi, 1994). Very little research has been devoted to rates of marine extinction peculiar to remote island ecosystems and it is conceivable that isolation in such circumstances may result in a vulnerability to extinction that is comparable to that in insular terrestrial ecosystems. As island marine assemblages are generally poorly known it is highly likely that introductions will remain unrecognised and that resulting extinctions will occur in the vacuum of ignorance.

In a more general sense, marine introductions are unlikely to be benign even if extinction is not an inevitable consequence of their occurrence. Conservation traditionally focuses on species-level issues however in many instances the definition of species is largely arbitrary. Hybridization between marine species is common (Palumbi, 1994), and as evidenced in this study, the divergence in some loci may be greater between populations than it is between species recognised from morphological characteristics. Despite the cosmopolitan nature of many marine species, diversity at the level of population may deserve an equal conservation effort to that devoted to species diversity. There is concern that the introduction of foreign gene-lines or sibling species may mask the decline of native populations (Geller, 1999) resulting in the loss of diversity and the homogenization of global meta-populations.

The loss of genetically distinct populations within a species is considered to be at least as important a problem as the loss of entire species (Crozier, 1997, Ehrlich, 1988). Impacts associated with hybridisation between isolated populations include: loss of adapted genes, loss of native populations through competitive displacement, homogenization of a previously structured population, and the failure of hybrid populations to re-adapt to local conditions (Ryman *et al*, 1995). The loss of fitness associated with hybridization has been referred to as "out-breeding depression". This fitness loss is at its most severe in hybrids of separate species; however significant effects can be detected between crosses of genetically different populations (Hindar, 1999).

The results of this study demonstrate that Southern Hemisphere populations of *M. galloprovincialis* fall into two discreet categories. Introduced populations, and also those populations resident within port locations offering the opportunity for frequent genetic exchange with Northern hemisphere stock are considered to belong to a large cosmopolitan clade that is globally distributed. Conversely, isolated regions have been shown to host populations that still hold a natural genetic structure with a unique Southern Hemisphere genotype. These unique genotypes represent an important example of genetic variation in a species complex that has become increasingly homogenized. Conservation efforts in the region should reflect that high latitude islands are at risk from marine introductions at the level of genes as well as the level of species. While mussel free islands such as Macquarie Island are clearly at risk from the

introduction of *M. galloprovincialis*, the unique populations of this species that naturally occur in the New Zealand sub-Antarctic are also at risk of invasion by foreign genotypes.

Acknowledgements

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Section III

Thermal Tolerance

Chapter 6: Assessment of thermal tolerance

Assessing the thermal tolerance of fouling communities: future marine pests for Antarctica?

Abstract

Modern shipping operations carry entrained assemblages of marine organisms which are frequently left behind in foreign coastlines where they may establish non-indigenous populations. An assessment of tolerance to short term changes in water temperature over a time scale replicating a specific voyage provides a useful tool for examining the survival of communities during transport across a latitudinal gradient. By subjecting mature temperate fouling communities to temperatures typical of the sub-Antarctic islands and Antarctica, a pool of high risk species found within the port of Hobart is identified. A range of species are demonstrated to be capable of surviving in the sub-Antarctic islands and up to eight species survived in water temperatures replicating Antarctica. While a portion of the high risk species were known to be invasive in other regions, many species were not known to have invaded new regions and thus pose a hazard that may be overlooked by conventional risk assessment strategies focusing on high risk species.

Introduction

Modern shipping operations continue to carry entrained assemblages of marine organisms which are frequently left behind in foreign ports or coastlines, where they can establish non-indigenous populations capable of causing significant ecological and economic impacts. The chain of events leading to the colonization of ships by fouling communities has been well studied (Railkin, 2004; Lewis *et al*, 2003), as has the impact of established NIS upon natural communities (Race, 1982; Walker & Kendrick, 1998; Hobbs & Mooney, 1998; Carlton, 2000). Less well understood is the response of fouling communities to the stresses of an ocean passage. The force of water passing over the hull of a vessel, and the change in ambient water temperature during transit, are the primary physical forces determining which species entrained on a vessel hull will be able to survive any particular voyage. While many sheltered micro-habitats on vessels, such as sea-chests and recessed areas, provide refuge for species vulnerable to sheer force (Coutts & Taylor, 2004), changes in ambient water temperature are an inescapable feature of transport in any north-south gradient. An assessment of tolerance to short term changes in water temperature over a time scale replicating a specific voyage provides a useful tool for examining the survival of communities during transport across a latitudinal gradient. By examining entire community responses to thermal change, species posing an introduction hazard can be separated from low hazard species within a typical fouling assemblage.

Predictive models and risk assessments which are able to determine which species potentially pose a concern for specific coastal ecosystems are key tools in the management of NIS. These approaches have primarily been based upon simple criteria such as comparisons of native and recipient bio-regions (Hilliard & Raaymakers, 1997; Hays & Hewitt, 1998; Lewis & Summerson, 2006), and an assessment of known thermal limits of key invasive species (Hays & Hewitt, 2000b). While the former approach serves to highlight regions that are likely to contribute NIS, and the later may identify known high risk invaders capable of surviving in a recipient region, neither approach in itself provides a realistic subset of species that may be capable of surviving the transition from one environment to another.

Predicting which species are capable of establishing in new regions is of particular importance when assessing risks to remote, highly valued coastal environments. In ecosystems such as the sub-Antarctic islands and Antarctica low temperatures, exposed high energy coastlines and sea-

ice create an extremely different environment to that typical of the temperate ports. Additionally, transport opportunities for marine introductions are restricted by the low levels of shipping traffic. While these differences can serve to exclude some organisms, they should not be assumed to provide an absolute barrier to NIS. While most well known invaders consist of a small subset of organisms well adapted to the conditions typical of port environments (Ruiz *et al*, 2000) the unique condition of the Southern Ocean might favour a different subset of organisms that are unpredictable. Furthermore, high latitude temperatures can not be assumed to represent a barrier for the many invasive species introduced to temperate Australian port from the Northern Hemisphere. Such species can possess natural ranges that extend to the Arctic sea-ice zone (e.g., *Undaria pinnatifida*).

In high latitude regions the rate at which species introduction occurs, and the species which are likely to establish are likely to be substantially different to patterns observed elsewhere. Thus transport pathways need to be examined with particular reference to local conditions. While management in temperate regions has focused upon only a few key invasive species, management in high latitude regions should include other species not generally considered as pest-species in an assessment of potential invaders due to the dramatically different environment (see Chapter 7). Due to the relatively low level of parallel human stressors such as pollution and coastal habitat modification, the impact associated with NIS represents perhaps the greatest threat to biological communities in this region.

The intention of this investigation was to explore a real-time simulation of an operating transport pathway. Vessels traveling between Hobart and the Southern Ocean are observed to carry diverse fouling assemblages including many species which are NIS in Tasmania or elsewhere in the world (Lewis *et al.*, 2003). Although limited observations demonstrate that entrained communities are able to survive prolonged voyages (specifically the voyage to the sub-Antarctic Heard Island; Lewis *et al.*, 2005) there is currently no available information on the ability of temperate species to survive for prolonged periods within the sub-Antarctic environment.

Despite its extreme environment, Antarctica's coasts may also be at threat from introduced species. While it is possible that sea-ice will scrape communities from the hull of vessels approaching Antarctica it is almost inevitable that some organisms will survive in sheltered regions of the vessel hull (see Coutts *et al*, 2003), and it is plausible that even individuals that are

scraped from the hull could eventually drift and settle into waters that are appropriate for survival. For instance, it has been suggested that hydroids are capable of successfully settling and establishing new populations in just this manner (Runeger, 1969).

To examine the ability of species to survive in high latitude environments, fouling communities naturally recruited in temperate conditions were maintained in aquariums at a range of temperatures that replicate the typical water conditions of Macquarie Island and Antarctica. For comparative purposes, communities were also exposed to temperatures typical of the Australian subtropical coastline. Although additional stresses in high latitude environments such as high wave energy, sea-ice formation and different native communities could not be tested in this experiment, the results address the most extreme environmental difference between temperate and high latitude coastal environments: temperature.

Methods

Collection of communities

Communities of fouling organisms were collected on 250 x 250 mm PVC settlement plates deployed in the Derwent River, Hobart, for an 18-20 month period (Figure 6.1). Established communities were then retrieved at two discreet intervals and transferred to aquarium facilities for experimental trials (Figure 6.2). Experiments were conducted in two stages to minimise the number of tanks required for the experiment.

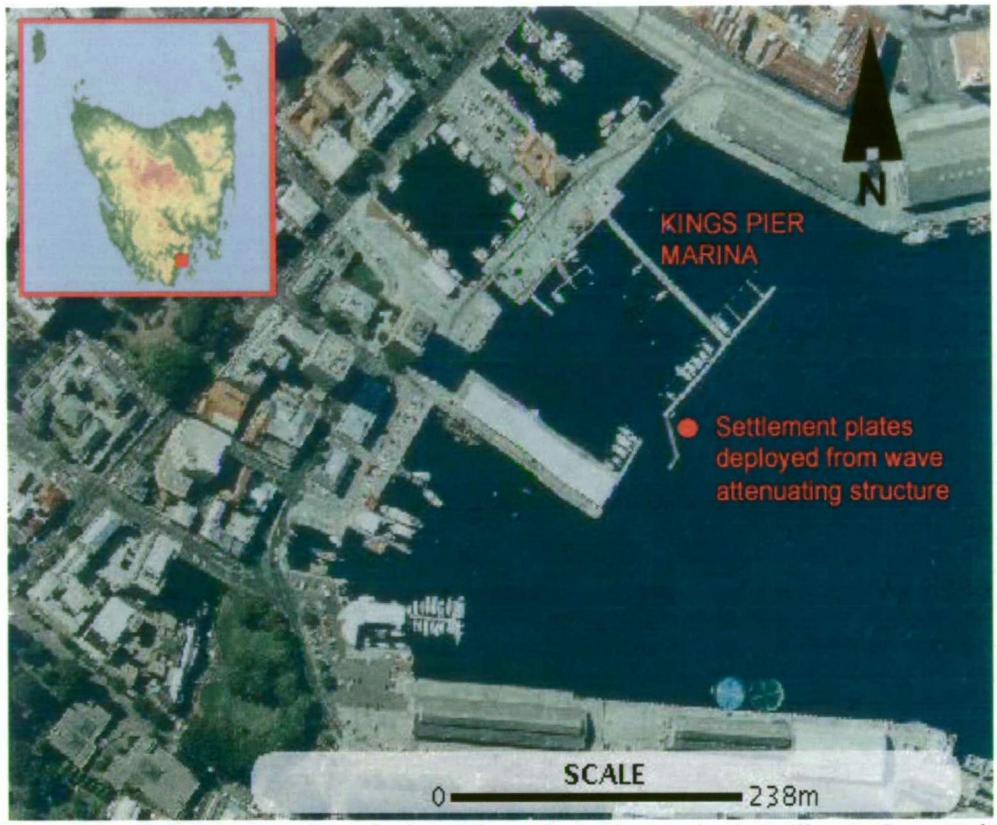


Figure 6.1: Location of settlement plates deployed from Kings Pier Marina in Sullivan's Cove, Hobart. Image modified from ListMap®

At each of the two collection dates 19 plates were retrieved by divers using SCUBA and placed into aerated plastic tanks for transport. Three of these 19 plates were retained to determine the diversity of organisms associated with the plates. This information was used to estimate the extent of variability between plates at the time of collection, and to compare the communities associated with the plates at the two collection dates. The remaining 16 plates were photographed to assess the percentage cover of dominant species, and wet community weight was measured to compare biomass. During these initial measurements, plates were handled carefully to ensure a minimum duration of emersion and associated stress.

Experimental trials

The 16 experimental plates used in each trial were housed in individual aquaria with four aquaria designated to each of four temperature preparations. Temperatures were chosen to replicate Antarctica (0ºC), the sub-Antarctic Macquarie Island (5ºC), subtropical Australia (25ºC) and a control temperate preparation of 13ºC. The four tanks allocated to each temperature group were positioned in an insulated bath of circulating water maintained at the desired temperature

through the use of chiller units and standard aquarium heaters. Before preparations were brought to the target temperatures, all aquaria were maintained at the ambient sea-temperature of 13ºC for a six day period to acclimate the communities to aquarium conditions. Following this period, each aquarium was slowly brought to the required experimental temperature over a period of 3-6 days (see Figure 6.2). This time scale was selected to replicate the approximate voyage times for vessels traveling from Hobart to Macquarie Island (3 days), and from Hobart to Antarctica or the subtropical coastline (6 days).

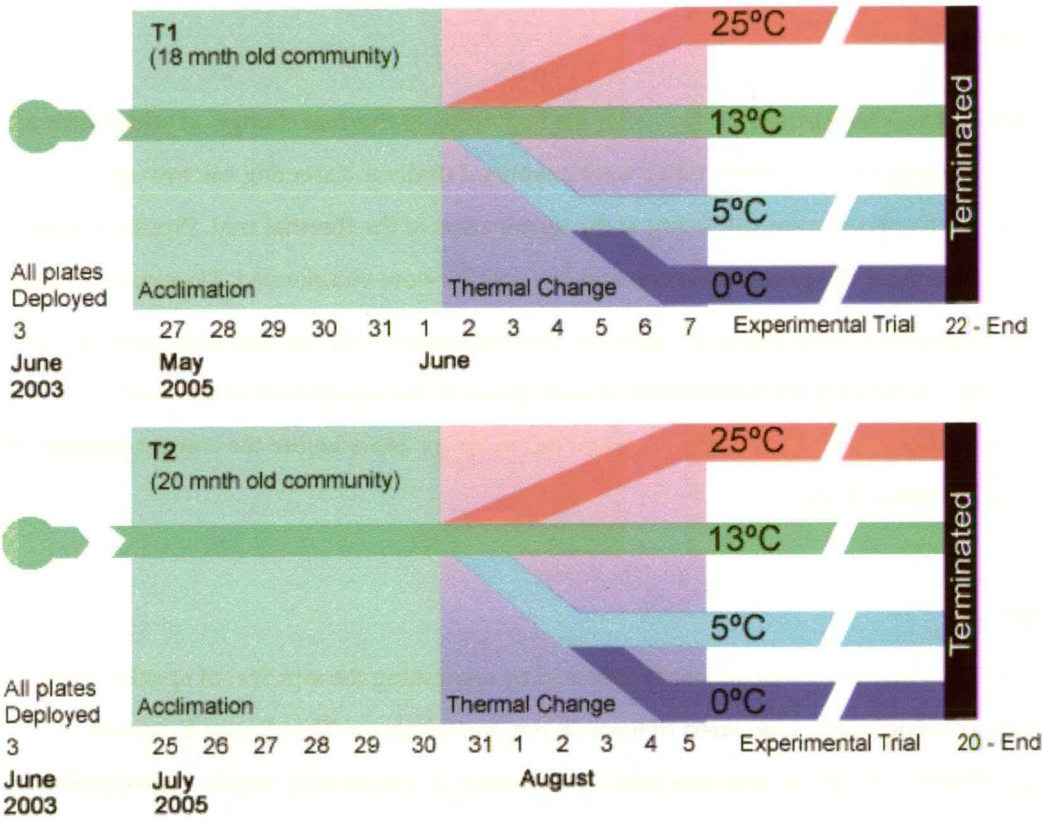


Figure 6.2: Time-line of experiment showing recruitment, collection, acclimation, thermal change and experimental time periods. Plates were collected and analysed in two series of experiments separated by two months to reduce the total aquaria being managed at any time. The two collection dates are referred to as Time 1 (T1) and Time 2 (T2).

Throughout the experiment each aquarium was fed predominantly upon a monoculture of the phytoplankton *Phaeodactylum tricornutum*, cultured at the Australian Antarctic Division. To provide a diverse food source, this culture was supplemented with a mix of "instant algae®" cultures of *Thallassiosira weissflogii, Pavlova sp.* and *Isochrysis sp.* Communities were fed daily according to the rate at which the water was cleared. Clarity was assessed qualitatively and

ranked from 0 - 1 with 1 representing completely clear water and 0 representing the initial state of water following the addition of 500mL of algal culture. Tanks were subsequently fed a quantity of algae that was directly proportion to the rate of clearing (i.e. tanks assessed with a rank of 1 were provided with 500 mL of algae, tanks assessed as 0.5 were provided with 250 mL of algae). Although feeding rates were identical during the acclimation period, rates later varied in response to community health. Tanks were subject to a 12 hour light/dark cycle and each aquarium was fitted with an air-stone to provide oxygenation and water flow. A 25% water change was conducted every two days with filtered sea-water adjusted to the correct temperature.

The experiment was terminated 21 days after the beginning of thermal change, at which time all plates were photographed. Communities were examined under a dissecting microscope to determine which species were still living at the termination of the thermal trial. Presence/absence data was collected for all species observed and key species were enumerated. Dominant species cover was determined using Image J® software and compared to the photographs taken prior to the experiment. Following the termination of each phase of the experiment tanks were thoroughly cleaned with nitric acid, rinsed, and left to air for 24hrs before the commencement of the next experimental trial.

Variables

The health of communities was primarily assessed by examining the survival of species in the experimental temperatures compared to those in the control group. The change in spatial coverage of dominant species was also used as a measure of community health. Water quality indicators were recorded throughout the experiment as an indirect measure of the response of the communities to the altered temperature. The pH (measured using a WTW electric probe) and the concentration of ammonia (NH^4- measured using an Aquarium Pharmaceuticals Inc. test kit) in the tanks was measured daily and a measure of nitrate (NO_3- measured using an Aquarium Pharmaceuticals Inc. test kit) was obtained every second day prior to the water change. Dissolved oxygen was monitored using Figaro® oxygen sensors logging at 10 minute intervals.

Basic observations of individual health for key species were recorded throughout the study. These included observations of movement and feeding activity in motile species, and the

response exhibited by filter feeding bivalves and ascidians which close their valves or operculum in response to stimuli. Any observations of spawning or reproduction were also recorded.

Analysis

Cluster analysis, non-metric Multidimensional Scaling (nMDS) and Similarity Percentage (SIMPER) using Primer software (Clarke & Gorley, 2006) were used to examine differences between communities. This approach was used to examine the uniformity of communities prior to the experiment and also to examine the effects of the experimental conditions following the conclusion of the trial. For these analyses, the data matrix was constructed using presence/absence data only and then converted to a symmetric matrix of biotic dissimilarity between pairs of experimental temperatures using the Bray-Curtis similarity index. The dissimilarity matrix was agglomeratively clustered using average linkage using 20 restarts. The usefulness of the two dimensional nMDS plot of relationships between sites is indicated by the stress statistic, which if <0.1 indicates that most of the three dimensional variability can be accurately displayed within two dimensions (Clarke, 1993).

The spatial coverage of dominant fouling species on the 16 plates used in each trial was employed to further examine the difference in communities prior to the trials and to examine any differences between the two collection dates (T1 and T2). The change in spatial coverage for key fouling species was assessed from before and after photographs using Image J ® software. The change in spatial distribution was assessed using the percentage cover in the final photographs compared to that recorded initially. The change in spatial coverage during the trial (expressed as % of original and square-root transformed) was analysed using nMDS and cluster analysis. Additionally, ANOSIM was used to compare the spatial coverage and diversity of assemblages between collection dates and also to compare initial communities to control assemblages.

Numbers of individuals of the two dominant species (the non-indigenous crustaceans *Petrolisthes elongatus* and *Halicarcinus innominatus*) in each tank was anlaysed by MANOVA using the program SPSS. A one-way ANOVA was used to examine the change in community weights and the difference in the physical parameters of pH, ammonia and nitrate were examined using repeated measures ANOVA's on the program. The variation across all recorded parameters and analysis was summarized through Principle Component Analysis (PCA) using SPSS software.

Results

Recruitment

Species Diversity

Species recorded from the plates gathered at both collection dates (T1 and T2) are presented in Table 6.1. A moderately diverse community representing a total of 50 species was identified in pre-trial plates. Figure 6.3 illustrates a cluster analysis demonstrating that the fauna associated with plates from the two collection dates were not unique and that the communities associated with the three plates from each time were at least 65% similar. The communities that survived the experiment within the control preparation are also included within the cluster anlaysis to assess the viability of the control in the experiment. There is no significant difference between communities at T1, T2 or the final communities in the control assemblages (ANOSIM Global R: 0.27) indicating that time of collection did not affect community composition, and that aquarium conditions did not contribute significantly to the survival of assemblages.

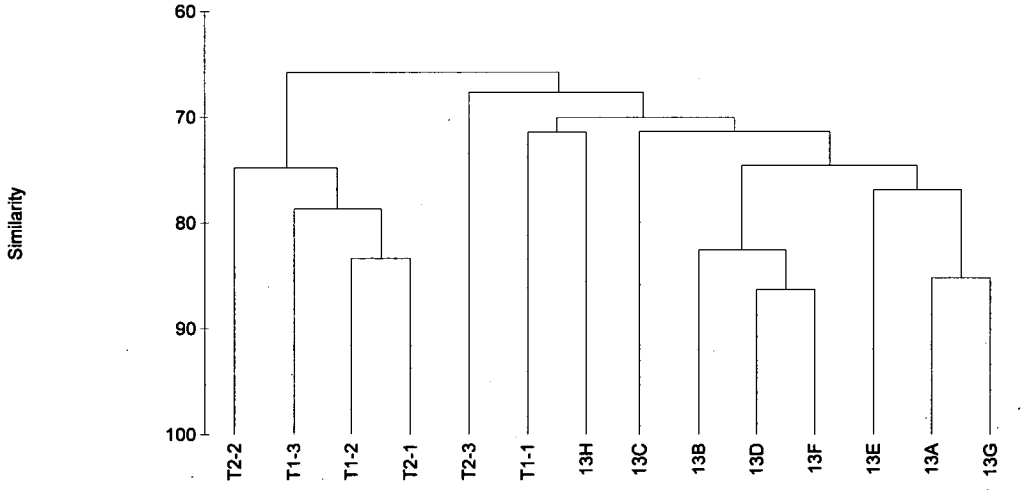


Figure 6.3: Cluster analysis demonstrating similarity of communities from plates collected prior to the experiment at T1 (May 2005; T1-1, T1-2, T1-3) and at T2 (July 2005; T2-1, T2-2, T2-3). Control plates from both times (13A-13H) are also included in the analysis to demonstrate the similarity in communities before and after the trial and the control plates.

An analysis of the differences that were observed between pre-trial plates and control plates using SIMPER reveals that a few species contribute similarly to the small observed differences. Although some species such as the introduced amphipod *Corophium acherusicum* and an unidentified species of bryozoan and hydroid occurred in one but not the other of the pre-trial groups, no single species stands out as a primary cause of the slight difference observed with several species contributing between 2.5% and 3.7% of the cumulative variability. Similarly, no species stand out as primary contributors to variability between the control and either of the pre-trial groups (individual species contributions range from 2.5% to 4.5%). It is of note that several species recorded in the pre-trial communities were not recorded in any of the control plates or any other plates that were subjected to experimental conditions. These included the amphipod *Corophium acherusicum*, two species of Porifera, an unidentified bryozoan and a Dorvelied polychaete. All these species only occurred rarely in the pre-trial communities.

Community Weight

A comparison of wet community weights shows that the weight of communities collected at T1 and T2 was not significantly different ($F = 1.917$; $p = 0.17$) and that variation in initial weights within each temperature preparation was also insignificant ($F = 0.165$; $p = 0.919$). The weight of all plates in each tank prior to the experiments is shown in Figure 6.4.

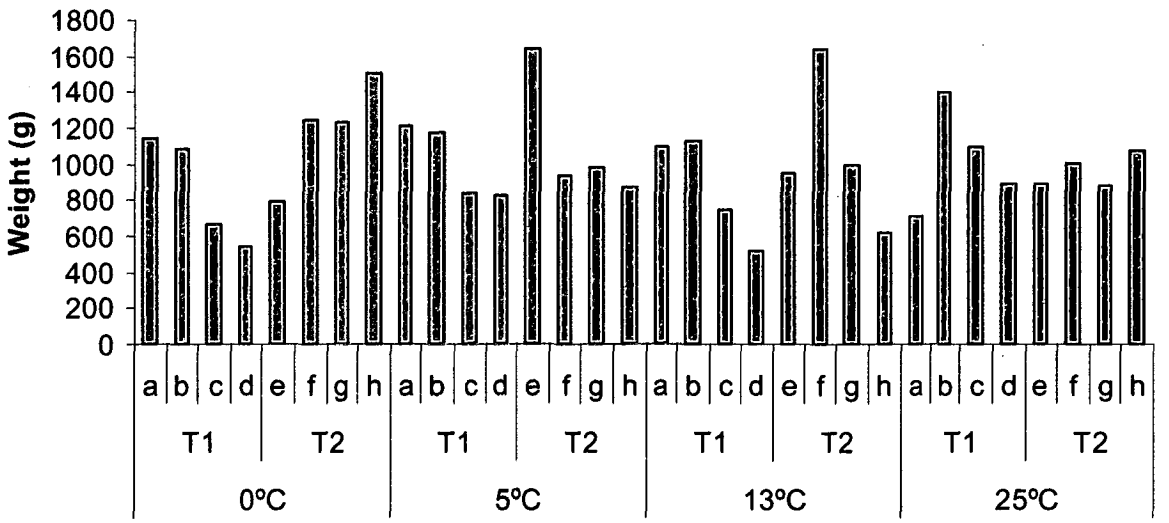


Figure 6.4: Wet-weight of communities recorded prior to the experiment.

Spatial Coverage

Figure 6.5 shows an nMDS plot based on the spatial coverage of the dominant habitat forming groups present on plates prior to the start of the experiment. Species counted were *Pyura stolinifera, Crassostrea gigas, Mytilus galloprovincialis* as well as a general category pertaining to other ascidian species that could not be identified in the images. All plates cluster in one general group demonstrating that communities are similar in their composition (Figure 6.5). Cluster analysis indicates that most communities are at least 85% similar however a single plate (25b) was found to be only 75% similar to the rest of the plates. SIMPER analysis indicated that this difference was primarily a result of the coverage of *P. stolinfera* on this plate which covered less area (147.1 cm^2) than the average of the other plates ($\bar{x}$ = 362.7 cm^2). ANOSIM demonstrated that despite this variability there is no significant difference between spatial coverage prior to the trials at any temperature or between any collection date (Global R: 0.061).

The assessment of species associated with the settlement plates, the weight of communities prior to the experiment and a comparison of spatial coverage by dominant species all demonstrate that the plates used in this experiment were colonised by a relatively homogenous community. No large differences were observed between plates at the two collection dates (T1 and T2) and as a result, plates have been treated as a single population except where significant differences between T1 and T2 are observed within particular analyses.

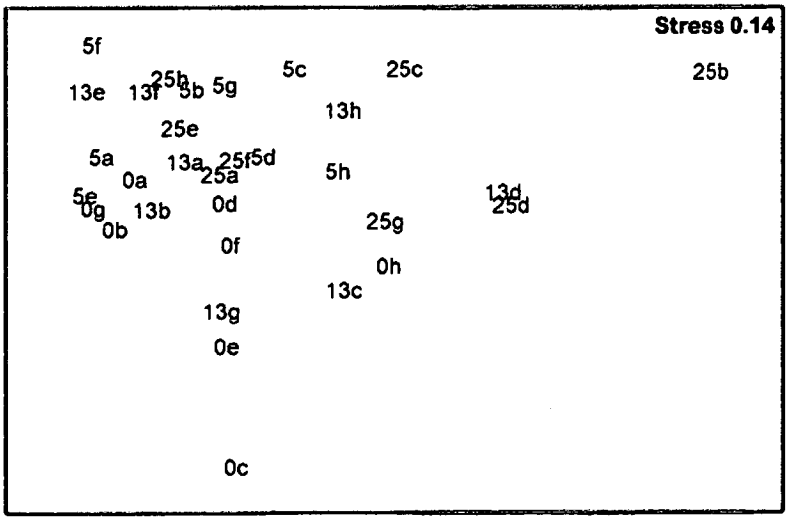


Figure 6.5: nMDS showing the similarity in the spatial coverage of all plates prior to the experiment. Numbers correspond to the temperature at which communities were maintained, and letters indicate replicates within each group.

Table 6.1: A list of all species recorded on the settlement plates. The table includes species associated with plates collected at T1 and T2 prior to the experiment, and all species recorded on the plates at each temperature following the conclusion of the experiment. Species with invasive characteristics are marked*.

		Pre-trial		Post – trial			
		T1	T2	0°C	5°C	13°C	25°C
Polychaeta	*Neanthes cricognatha*	X	X		X	X	X
	Boccardia polybranchia	X	X		X	X	
	Ophiodromus sp.	X	X		X	X	
	Harmothoe waahli	X	X	X	X	X	X
	Polynoidae sp1	X	X	X	X	X	
	Pomatoceros taeniata	X	X		X	X	
	Cirriformia sp.	X	X		X	X	X
	Spirorbid sp.	X	X			X	X
	Dorvelleid sp.	X					
Hirudinea	Hirudinea sp.		X			X	
Platyhemlenthes	*Notoplana australis*	X	X		X	X	X
Amphipoda	*Ericthonius sp.*	X	X		X	X	
	Parawaldeckia sp.	X	X		X	X	
	*Corophium acherusicum**	X					
Isopoda	*Munida sp.*	X	X			X	
	Sphaeromatidae sp1	X	X	X	X	X	
Crustacea	*Petrolisthes elongatus**	X	X		X	X	X
	*Halicarcinus inomminatus**	X	X		X	X	X
	Pinnotheres hickmani	X	X		X	X	X
	Notomithrax minor	X	X			X	
	Palaemon intermedius	X	X		X	X	
	Palaemon dolospina	X	X		X	X	
	Halicarcinus ovatus	X	X			X	
	Balanus variegates	X	X	X	X	X	X
	*Elminius modestus**	X	X			X	X
Mollusca	*Irus (Irus) cumingii*	X	X			X	
	*Mytilus galloprovincialius**	X	X	X	X	X	X
	*Crassostrea gigas**	X	X	X	X	X	X
	Hiatella australis	X	X		X	X	X
	Nudibranch sp1	X	X			X	
	Aplysia sydneyensis	X	X		X	X	
	Muscula impacta	X	X			X	
Bryozoa	*Watersiporia subtorquata**	X	X		X	X	
	*Bugula flabellata**	X	X		X	X	X
	Bryozoa sp1	X	X			X	
	Bryozoa sp2		X				
Hydroid	Hydroid sp1	X	X			X	
	Hydroid sp2	X	X				
	Clytia sp.	X	X		X		
Ascidiacea	*Ciona intestinalis**	X	X	X	X	X	X
	Pyura stolonifera	X	X		X	X	
	*Botrylloides leachii**	X	X		X	X	X
	Cnemidocarpa radicosa	X	X			X	
	Herdmania momus	X	X	X	X	X	
	Ascidian sp1	X	X		X	X	X
Echinodermata	*Pateriella regularis**	X	X		X	X	
Porifera	Porifera sp1	X	X			X	
	Porifera sp2	X	X			X	
	Porifera sp3	X	X				
	Porifera sp4		X				
TOTAL SPECIES		47	48	8	30	43	17

Community Survival

Species Diversity

The number of species surviving in each tank during each trial is presented in Figure 6.6 (see Appendix 1 for a list of all species recorded in each trial). A total of 44 species were recorded in the communities following the termination of the thermal trials (see Table 6.1). The highest number of species was recorded in the temperate 13ºC control tanks (43) followed by the sub-Antarctic 5ºC tanks (30), the 25ºC subtropical tank (17) and the 0ºC Antarctic preparation (8). A total of 11 species introduced to a number of continents were recorded from the post-trial communities.

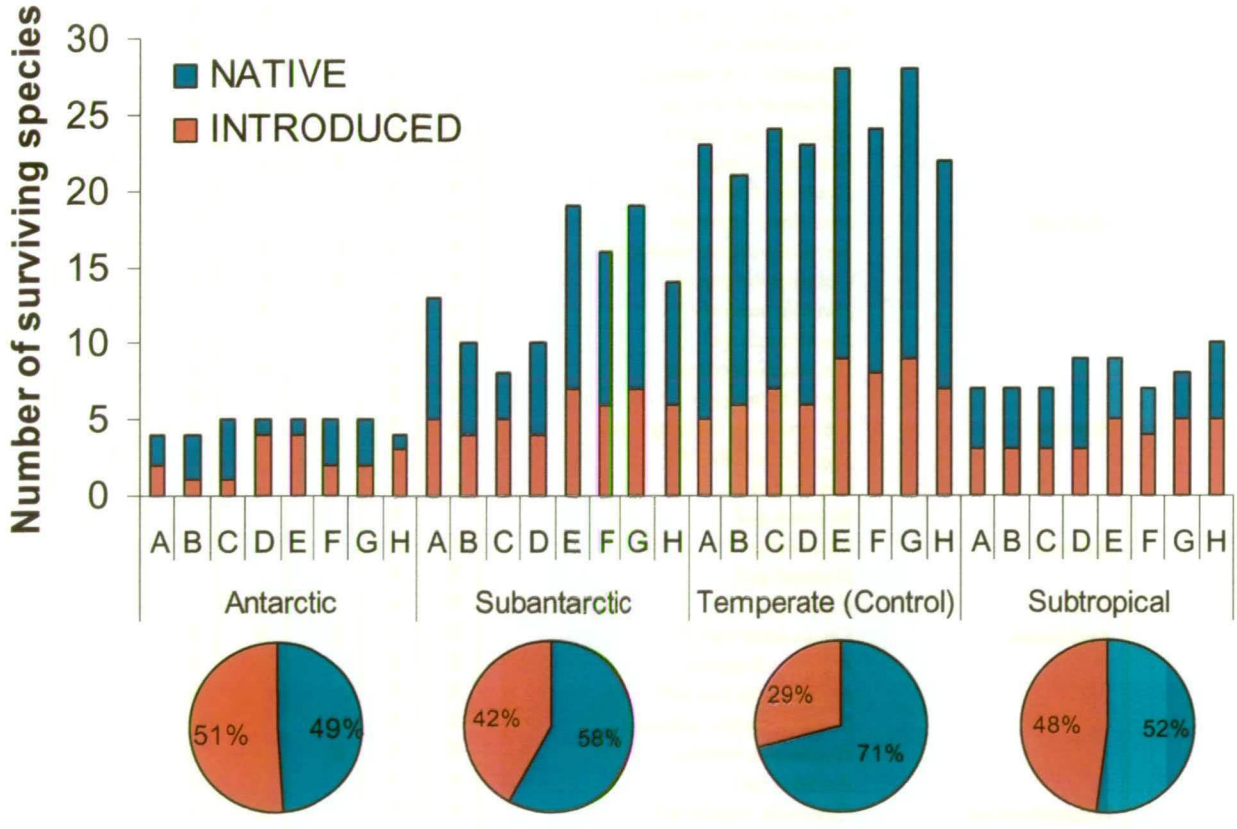


Figure 6.6: Total species recorded in each tank at each temperature. Red portions of the bars indicate the proportion of species which have established non-indigenous populations. Mean proportions of native: non-indigenous species in each temperature group are provided in the pie graphs.

Within temperature groups, control units again possessed the greatest diversity (up to 28 species - see Figure 6.6). Assemblages of up to 19 species were capable of surviving at the reduced temperature of 5ºC, and assemblages of up to 5 and 10 species were able to survive in the 0ºC and 25ºC preparations respectively. In each of these surviving assemblages, NIS represent a significant portion of the assemblage, and mortality was more evident in native species than in non-indigenous organisms. The relatively high rate of survival in NIS resulted in experimental communities with a higher proportion of NIS than was recorded in the control preparations. The Antarctic aquaria retained the greatest proportion of NIS (51%), followed by the subtropical (48%) and sub-Antarctic (42%) communities. While surviving native species declined in the 5ºC preparation, the number of NIS remained comparable to the control preparations with 6-8 NIS present compared to 7-9 NIS recorded in the control. NIS comprised 29% of the species recorded in the control group, a similar proportion to that recorded in the initial communities observed on non-experimental plates (16.7-25.8%: see Appendix 1).

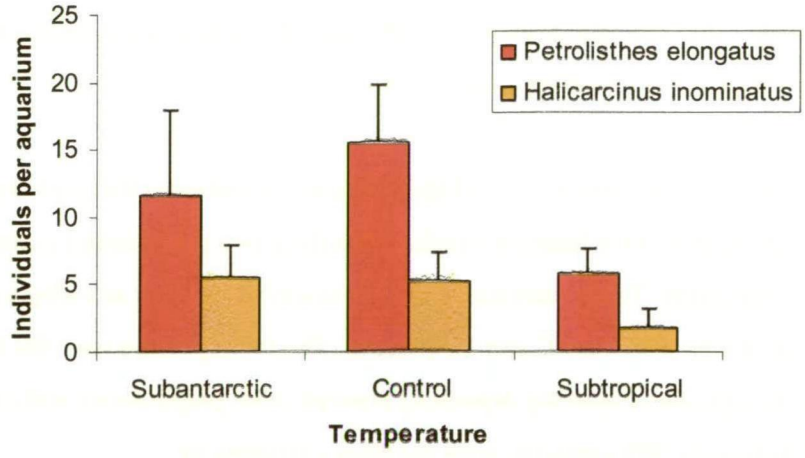


Figure 6.7: Mean number of non-indigenous crabs recorded in the 5°C, 13°C and 25°C tanks. Error bars show standard deviation.

Although NIS of molluscs (*Mytilus galloprovincialis*[3], *Crassostrea gigas*) and ascidians (*Ciona intestinalis*) represented some of the few surviving individuals recorded in the Antarctic preparation, no crustaceans survived when maintained at 0ºC. Two crustaceans, the introduced Hymenosommatid crab *Halicarcinus inominatus* and the Anomuran *Petrolisthes elongatus* were numerically dominant in the surviving communities of all other preparations, with *P. elongatus* the dominant species in all instances (see Figure 6.7). Temperature was observed to significantly affect the density of both these species in the 5ºC. 13ºC and 25ºC tanks ($F = 5.35$ $p = 0.01$). Numbers of *H. inominatus* and *P. elongatus* were similar in the control and the sub-Antarctic preparation (shown as a single homogenous subset in Tukey's post-hoc analysis), but fewer individuals of both species survived in the subtropical group.

The nMDS analysis of presence/absence data showed that replicate tanks within each temperature possessed a high level of faunistic coherence compared to samples maintained at alternative temperatures, indicating that a distinct community of species was able to survive at each temperature (Figure 6.8). The nMDS shows that replicates from the 5ºC and 13ºC tanks formed a distinct group relative to the other temperatures. The stress value associated with the nMDS is 0.1 which suggests that this pattern is a highly useful representation of the faunal patterns between tanks. Thus the close proximity of 5ºC and 13ºC reflects a real similarity in the assemblage that survived at these temperatures.

This grouping is supported by cluster analysis (Figure 6.9), which indicates that replicate trials at 5ºC and 13ºC showed a high level of faunistic overlap with these two preparations clustering in a single unit with 65% similarity. Tanks maintained at 25ºC clustered together as a single unit that shared only a 50% similarity with the 5ºC and 13ºC cluster. The 0ºC replicates were the most dissimilar group with replicates clustering separately from all other preparations and clustering in a loose group sharing only 30% similarity with the other preparations.

[3] *Mytilus galloprovincialis* is native to the temperate communities of Hobart but is considered an invasive species in South Africa and should be considered as a potentially invasive species in high latitude regions, but see Chapter 4.

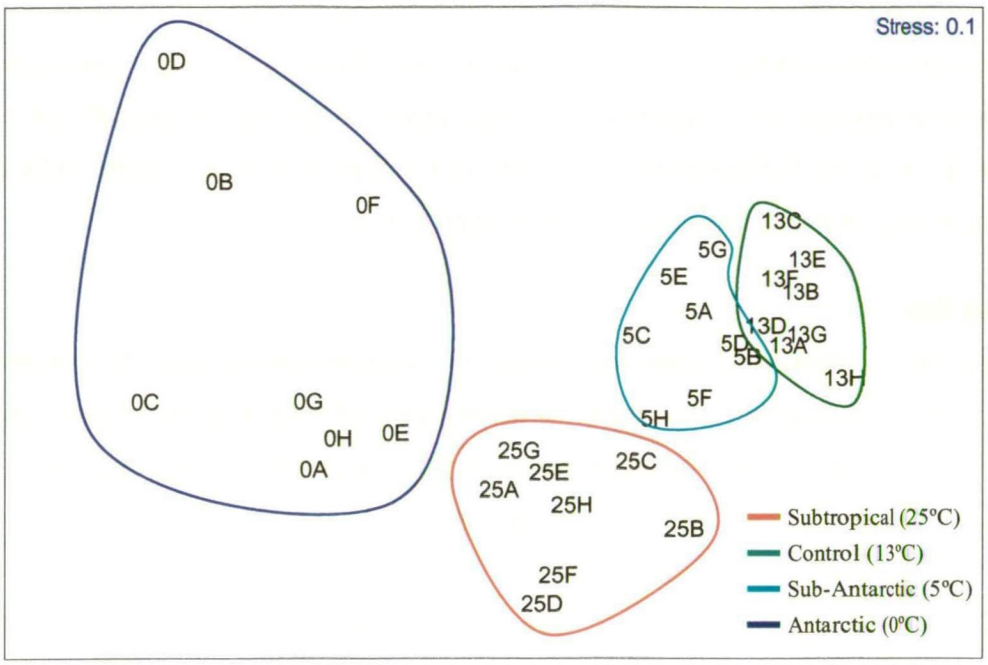


Figure 6.8: nMDS plot of the differences in communities associated with each temperature group. Dark blue = 0°C aquariums; red = 25°C aquariums; light blue = 5°C aquariums and green = 13°C

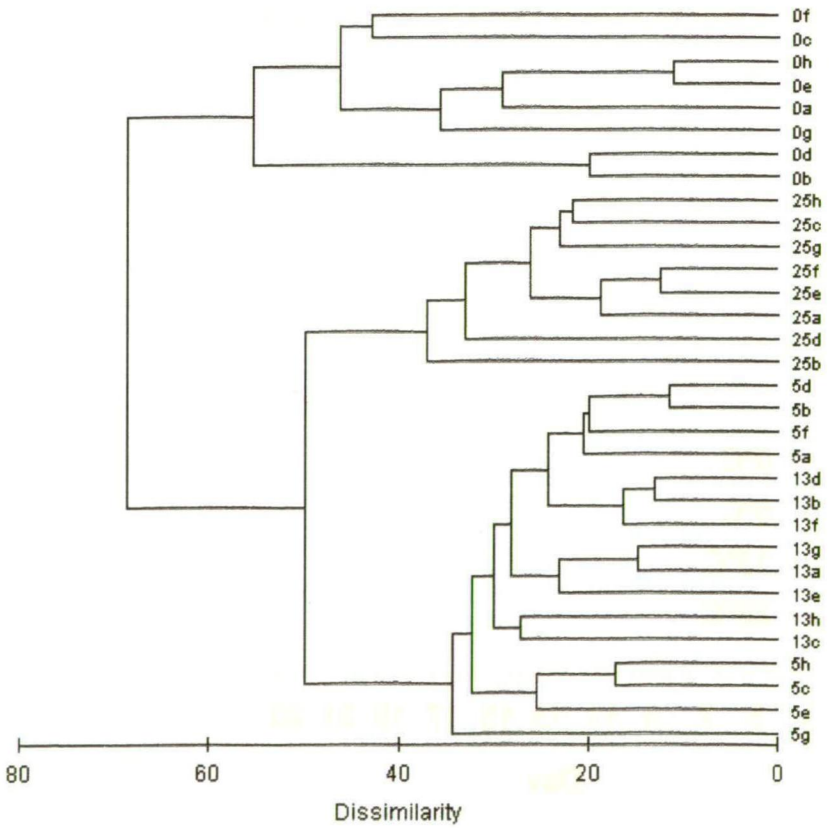


Figure 6.9: Cluster analysis showing dissimilarity between communities, based on presence/absence within each tank.

Analysis of similarity (ANOSIM) provides a robust Global R statistic of 0.73 ($p = 0.01$), indicating a positive temperature effect. Pair-wise tests of each group confirm that 5ºC and 13ºC are most similar ($R = 49$; $p = 0.01$) followed by 25ºC and 0ºC ($R = 0.66$; $p = 0.01$). Communities within these two subgroups are highly dissimilar from each other ($R > 0.8$).

Feeding Rate

Feeding rate was measured qualitatively through a visual assessment of water clarity scored from 0 to 1, with 0 indicating the state of the water following the addition of 500 mL of algal culture. Mean clarity scores for each temperature are provided in Figure 6.10 (T1 and T2 have been pooled). Tanks maintained in the control temperature (13ºC) continued to completely clear the water throughout the experiment while the rate of feeding in the other tanks was reduced. Tanks at 25ºC initially cleared the water as effectively as the control but eventually the rate of feeding dropped significantly. The 0ºC and 5ºC tanks showed an early reduction in feeding rate, however the sub-Antarctic group continued to feed at a relatively high rate while the Antarctic tanks dropped to the lowest feeding rates recorded by day 16 before rising again to similar levels to that recorded in the 25ºC tanks.

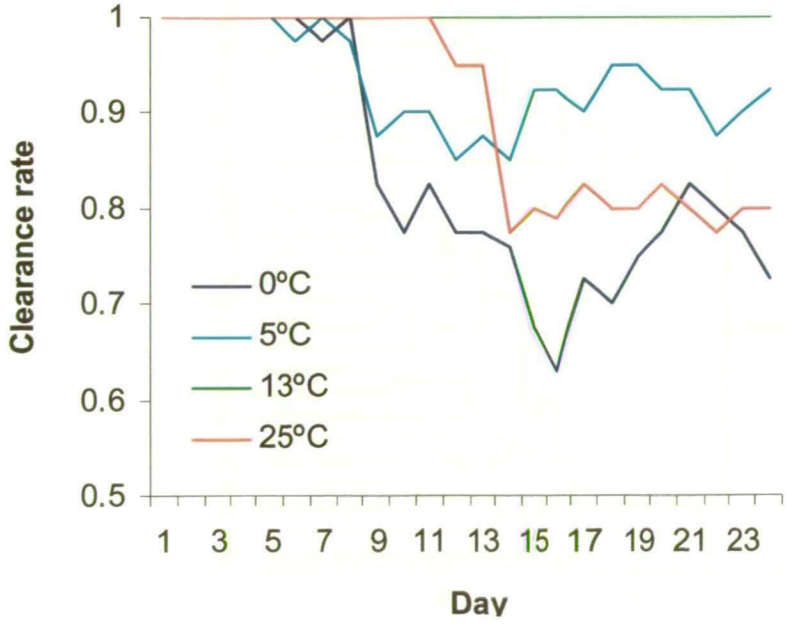


Figure 6.10: Mean clarity in each temperature group reflecting the rate of feeding in the communities.

Weight Change

The change in weight of fouling communities was highly significant ($F= 62.8$; $p<0.009$), however it was not highly informative regarding the relative response of the communities at different temperatures. The significant difference was primarily a result of high mortality in all communities maintained at 25ºC. The high loss in community weight in this preparation (mean weight change = 741.3) was far beyond that recorded in other temperature groups. This massive loss was attributable to the death of a single dominant species, *Pyura stolonifera,* which formed the primary superstructure in all communities. It should also be noted that this species contributed substantially to the community weight of the 0ºC plates, but subsequent dissections and observations in-situ showed that this species was only able to survive in 13ºC and 5ºC temperature preparations. While the species did not exhibit advanced decay at 0ºC, the individuals stopped feeding and subsequently died. As this species formed the primary habitat matrix on the plates, and due to potential stress on other organisms, individuals were not removed from the 0ºC plates and thus contribute substantially to the recorded weight despite their moribund status.

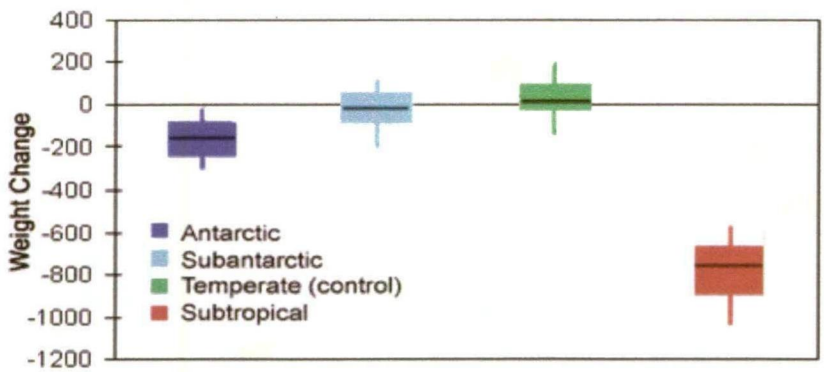


Figure 6.11: Box and whisker chart showing weight change recorded in each tank within each temperature group.

The weight change in the 0ºC, 5ºC and 13ºC tanks followed a gradient according to the relative difference in temperatures from the control preparation (see Figure 6.11). Mean weight changes in 0ºC, 5ºC and 13ºC were -138.4 g, -66 g and -10.2g respectively. Although some instances of positive weight gains were recorded in the 5ºC and 13ºC preparations there was generally a loss

of weight in all tanks probably reflecting the feeding of species upon each other during the trials, but also possibly reflecting death from other unknown causes.

Spatial Change

The change in spatial coverage of dominant species recorded from before and after photographs of the community was relatively uninformative due to dominance of only three sessile species and the ability of these species to survive in most of the temperatures used in the study. These dominant species only exhibited significant decay, and thus a reduction in spatial coverage, in the 25ºC temperature preparation. Other temperatures were >80% similar while all 25ºC separated distinctly from this group and also relatively distinctly from each other (see Figure 6.12). As noted above, *Pyura stolonifera* was also considered moribund at 0ºC yet, while rotting individuals were easily removed from the 25ºC plates, they were left in-situ in the 0ºC tanks and thus despite being dead, contributed to the % cover data for the 0ºC tanks.

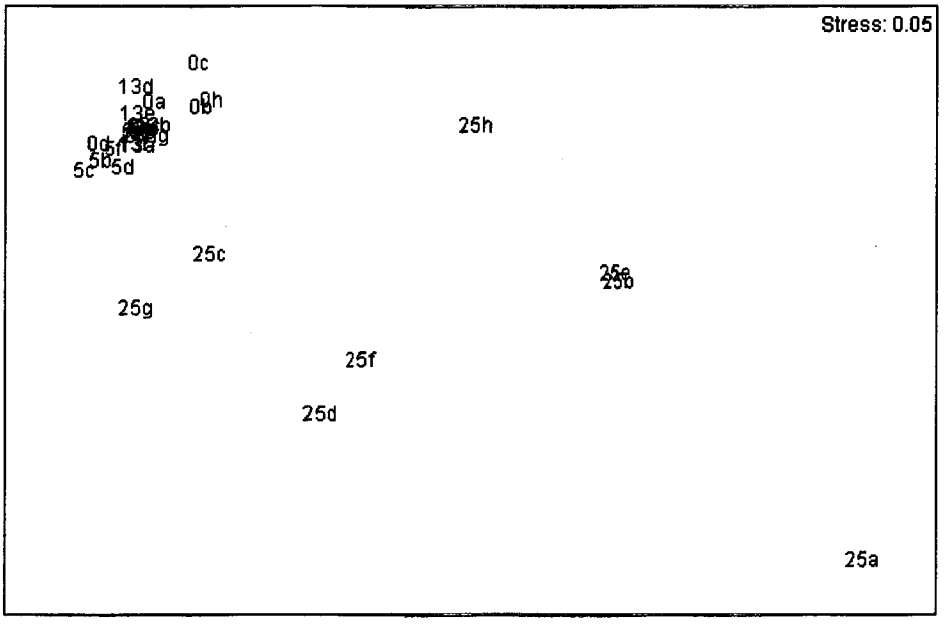


Figure 6.12: nMDS plot showing the difference between spatial coverage of key species within each temperature before and after the trial. This figure is included to demonstrate that only tanks maintained at 25°C fall outside of the tight cluster of tanks shown in the top right.

Behavioral observations

Observations of behaviour in motile species and species that display a visible response to external stimuli also contributed to the assessment of community state at the various temperatures. These observations supported the quantitative data collected. For instance, *Mytilus galloprovincialis* and *Pyura stolonifera* both ceased to respond to stimuli in the 0ºC and the 25ºC tanks 5-8 days after the target temperature was reached. Although motile crustaceans continued to be observed in the 25ºC tanks throughout the experiment, all motile crustacean were observed to be dead in the 0ºC tanks after only 5 days at the target temperature (although the barnacle *Balanus variegatus* survived at this temperature). Response to external stimuli in the 13ºC and 5ºC was observed throughout the experiment for sessile filter feeders, and crustaceans and polychaete worms were active in these tanks for the duration of the experiment.

Some spawning was also recorded in tanks maintained at 13ºC, 5 ºC and 0ºC and larvae of the introduced Amnuran *Petrolisthes elongatus* (Figure 6.13) and the introduced Hymenosamoatid crab *Halicarcinus innominatus* (Figure 6.14) were collected in several tanks maintained at 5º and 13ºC. The mussel *Mytilus galloprovincialis* was observed to spawn and settle in tanks maintained 5ºC and 13ºC and also in the 0ºC tanks prior to the eventual cessation of feeding activity at this temperature.

Figure 6.13: Larvae of *Petrolisthes elongatus* collected from 5°C tank

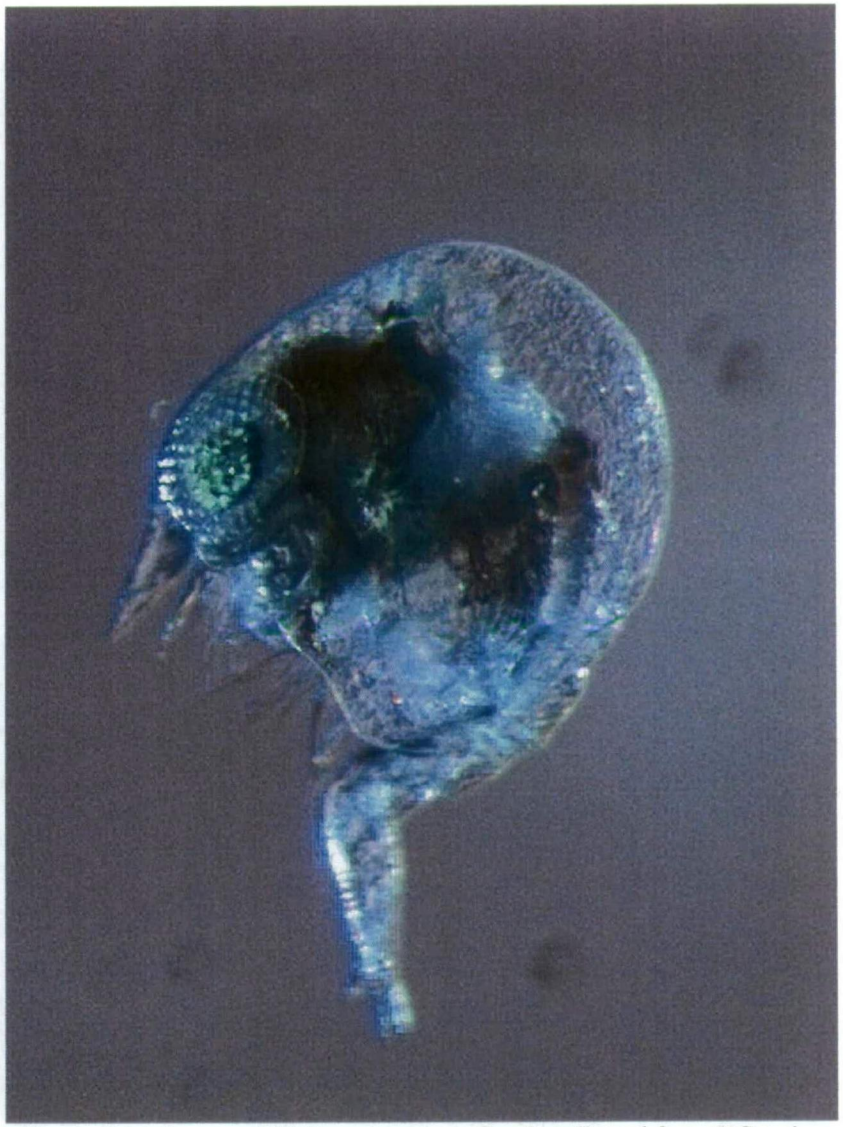


Figure 6.14: Larvae of *Halicarcinus innominatis* collected from 5°C tank

Physical Parameters

Ammonia

Levels of NH^4 were significantly higher ($F = 14.2$; $p < 0.009$), in the 25ºC preparations than all other temperature groups (Figure 6.15), and the two trials at this temperature were also significantly different from each other (Tukey HSD $p < 0.009$). Levels of NH^4 in the initial 25ºC trial were similar to other temperature groups until rising sharply on day 15. In contrast, ammonia began to increase after 9 days in the second 25ºC trial however both trials converged on similar ammonia levels by day 19. Levels of ammonia in other trials were not significantly different either within consecutive preparations of the same temperature, or between the three thermal groups (T1 and T2 have been pooled in Figure 6.15). Although non-significant ($p=0.895$), Figure 6.15 shows that levels of ammonia in preparations maintained at 0ºC were slightly higher than 5ºC and 13ºC.

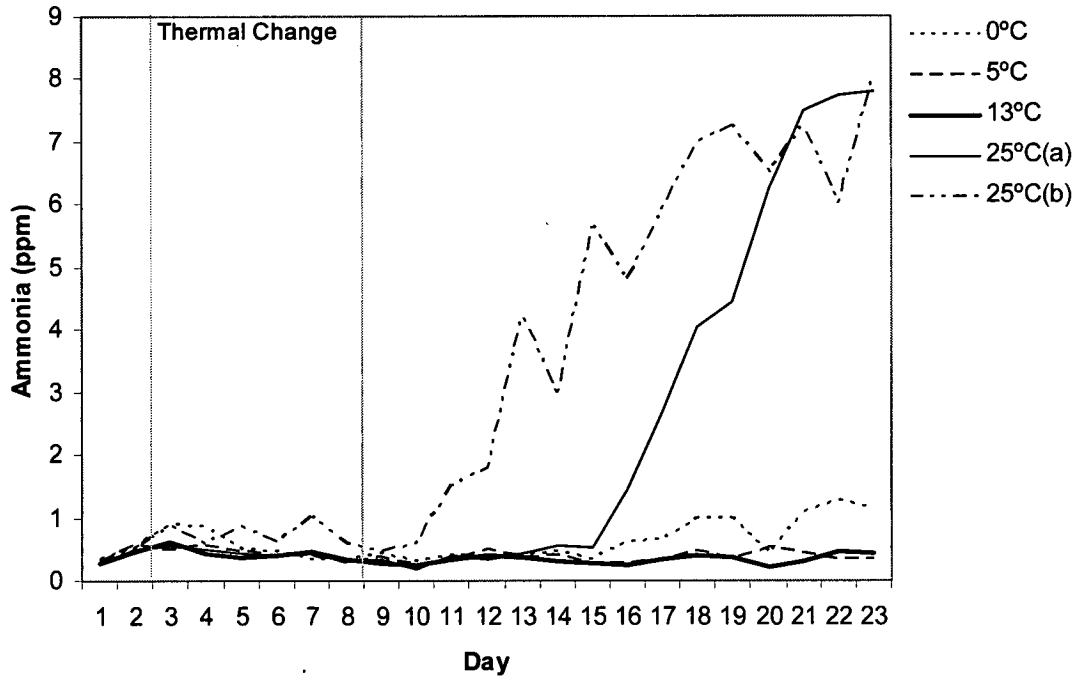


Figure 6.15: Mean levels of ammonia in tanks at each temperature. T1 and T2 have been pooled in all preparations except the 25ºC tanks which were significantly different.

Nitrate

Levels of nitrate in the 25ºC aquariums were significantly higher than those recorded in other temperatures (F = 2.668; p = 0.000). Levels in the 25ºC tanks rose sharply throughout the acclimation period and reached a peak of >20 ppm after only 9 days (see Figure 6.16). There was no significant difference between trials within temperature groups and results from T1 and T2 have been pooled in Figure 6.16. The control tank (13ºC) maintained moderate levels of nitrate (5-10 ppm) throughout the experiment, while nitrate in 0ºC and 5ºC remained close to, or below 5 ppm. Despite this small difference, Tukey's HSD post-hoc analysis indicates that 0ºC, 5ºC and 13ºC belong to a singular homogenous subset.

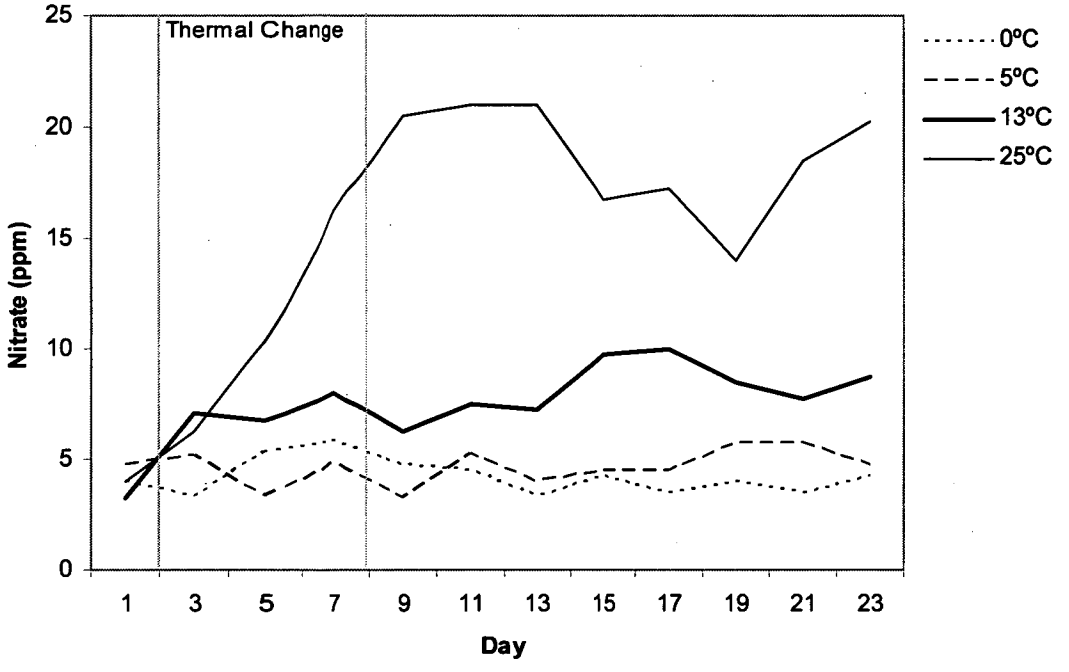


Figure 6.16: Mean levels of nitrate in tanks at each temperature. T1 and T2 have been pooled in most preparations except the 25°C tanks which were significantly different.

pH

The mean change in pH at each temperature is illustrated in Figure 6.17. The results of the two separate trials for each temperature have been pooled due to the absence of any significant difference in the two trials of any thermal group as discriminated by Tukey's HSD analysis (significance: $P_0 = 0.17$; $P_5=0.20$; $P_{13}=0.99$; P_{25}: 0.78). The relationship between time and temperature

was found to be significant ($F = 2.2$, $p < 0.009$), and it is clear from Figure 6.17 that the maintenance of communities at 25ºC resulted in more acidic water conditions possibly reflecting a higher rate of mortality and decomposition. The difference in the pH between the 25ºC preparations and the other temperature groups is supported by the homogenous subsets identified by Tukey's HSD analysis which grouped the two 25ºC preparations in a separate subset from the other temperatures.

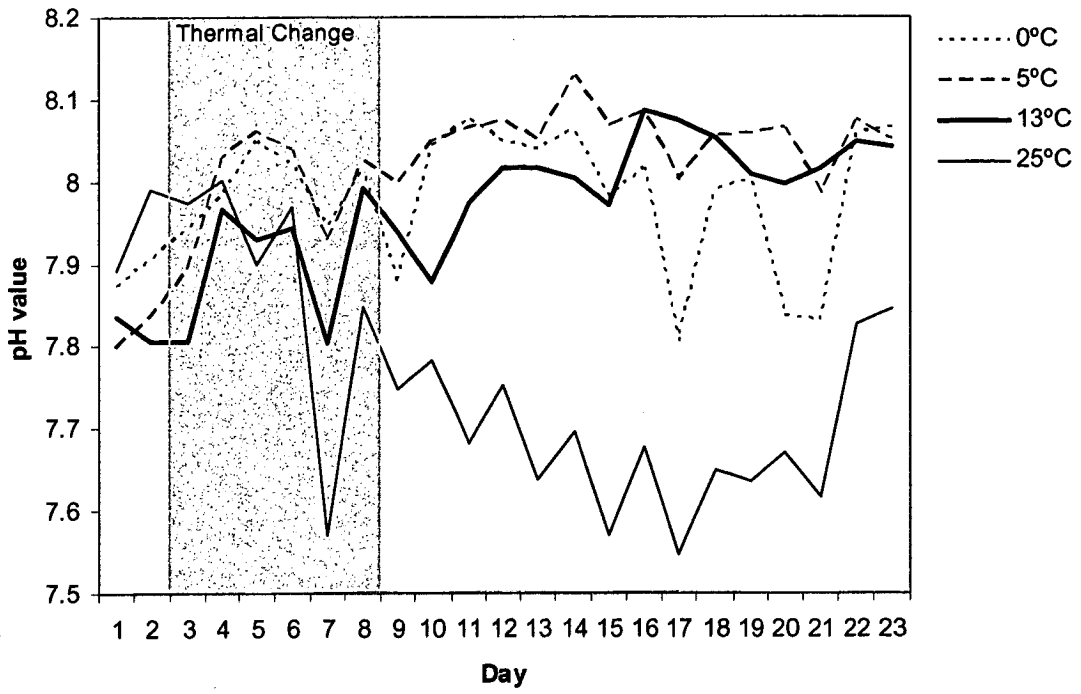


Figure 6.17: Mean pH levels at each temperature. T1 and T2 have been pooled in most preparations except the 25°C tanks which were significantly different.

Principle Component Analysis

The relative health of the communities were examined using the chemical measures of water quality collected throughout the experiment and an assessment of the diversity and composition of surviving organisms after 20 days at the target temperature. The variation across all recorded parameters has been summarised through Principle Component Analysis (PCA) (Figure 6.18). Most of the variation between tanks is attributable to Principle Component 1 which contributes 66.5% of the cumulative variability. The Eigen vectors for PC1 demonstrate that this variation is primarily attributable to differences in water chemistry with pH (0.52), NO_3 (0.56) and NH^4 (0.58) contributing equally towards the variability on this axis. PC2 contributes 22.4% of the variability

and relates to the number of species recorded in the tanks (Eigen vector for PC2, species = 0.94). A third principle component contributed 9.5% of the total variability related to pH (Eigen vector = 0.84).

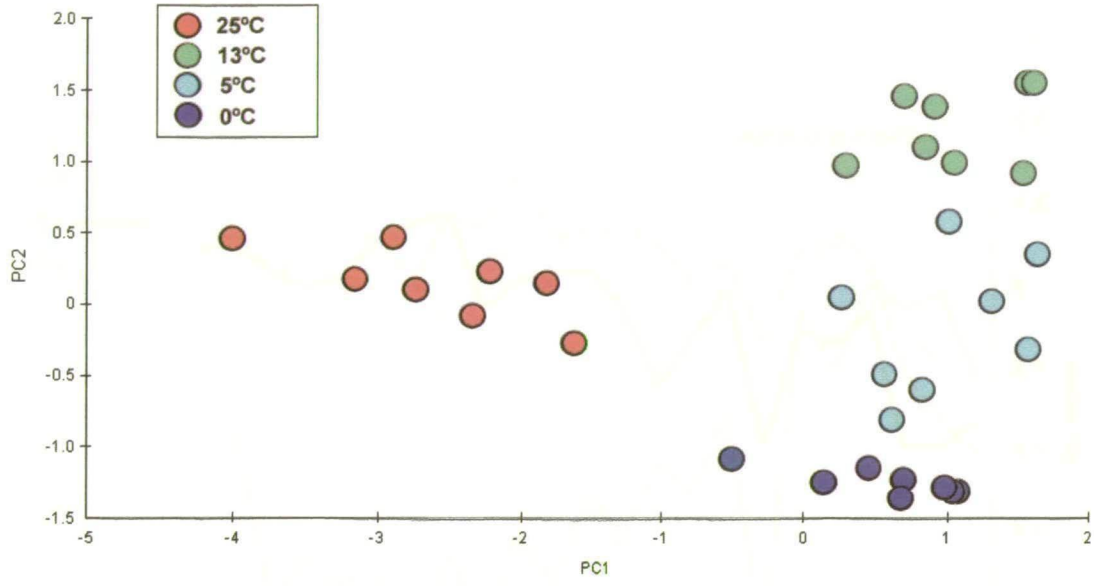


Figure 6.18: PCA based on the biological and chemical differences between the three thermal preparations.

The PCA plot clearly shows that differences in the final water chemistry (PC1) separate the cooler tanks and the control from the 25ºC preparations. A clear gradient over PC2 is revealed within the cooler tanks and the control preparation; with control tanks hosting the highest diversity of surviving organisms, followed by the sub-Antarctic tanks and Antarctic tanks which possessed the lowest diversity.

Discussion

A pool of potential invasive marine species for Antarctica and the sub-Antarctic islands has been described by simulating the transition in water temperature during a voyage from a temperate port to high latitude coastlines. Assemblages similar to those documented in hull fouling communities on Southern Ocean vessels (Lewis *et al*, 2003; 2005) were shown to include a range of species capable of surviving in temperatures well beyond the extremes typical of their local

environment. Of a total of 50 species recorded in initial fouling communities, 30 species were capable of surviving in sub-Antarctic (5ºC) waters temperatures, and eight species were capable of surviving the extreme transition from temperate (13ºC) to Antarctic (0ºC) temperatures.

The species that represent an introduction hazard to each region examined in this study are illustrated in Figure 6.19. Additionally, a species-specific risk was allocated to each species based upon the range of temperatures at which survival was demonstrated. Thus species surviving three experimental temperatures were designated high risk, species surviving two temperatures as medium risk and species surviving at only one experimental temperature were allocated a low risk. These categories are largely an indication of the potential for broad patterns of invasiveness in these species, and it is of note that three of the five "High Risk" species have already been introduced to a broad range of locations (i.e. *Crassosstrea gigas, Mytilus galloprovincialis,* and *Ciona intestinalis;* see NIMPIS, 2006). It should be recognised that "Low Risk" species shown as capable of survival in any one location may represent a very real threat to that specific region. Although the scope of this experiment is insufficient to demonstrate whether these species are capable of survival and reproduction in the recipient region, these species are likely to be alive upon arrival in these regions and to persist for an extended period. Any monitoring programmes should focus on these species in addition to high risk invasive species documented from donor port regions.

NIS were a common component in all communities recruited to the settlement plates used in the current study. While the proportion of surviving NIS in the control (13ºC) tank remained comparable to that observed in initial communities, a higher rate of mortality of native species relative to introduced species resulted in all other tanks hosting a community dominated numerically by invasive or NIS. Such species are likely to have been able to survive previous transitions between regions, and their tolerance to changes in ambient water temperature is likely to have played a major role in their success in establishing alien populations.

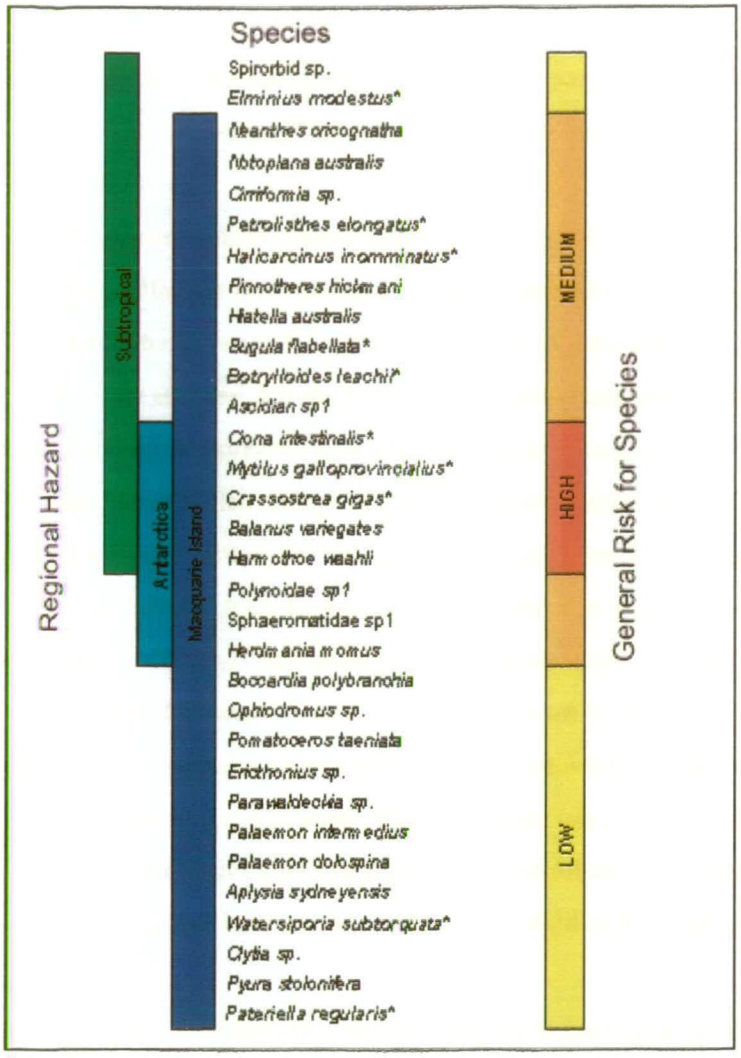


Figure 6.19: Species representing a hazard to each region, and a general assessment of risk for each species. Species able to survive at each region are indicated by the bar on the left. The breadth of thermal tolerance of species is indicated by the risk rating on the right. Species with invasive characteristics are marked *.

The high rate of survival in NIS relative to native species is particularly evident within the sub-Antarctic (5ºC) aquariums. The surviving assemblage at 5ºC was very similar to the control (13ºC) both in terms of the number of introduced species and the number of surviving individuals. Conversely, native species declined or disappeared at 5ºC relative to the control, resulting a numerical dominance of NIS within the sub-Antarctic assemblage. Despite the loss of some species at sub-Antarctic temperatures, 21 native species were still capable of survival at sub-Antarctic temperatures in addition to the NIS. Thus a broad range of species typically recruiting

to temperate fouling assemblages should be considered a high hazard for introduction into sub-Antarctic ecosystems. While these high risk species include nine NIS, it is important to note that many native species were also capable of survival at 5ºC.

Antarctic temperatures represent an environmental extreme well beyond any encountered in temperate regions and it was predictable that these assemblages would suffer the highest rate of mortality. The fact that eight species were able to survive this temperature transition highlights that even extreme environmental differences should not be a cause for complacency when assessing the potential for introductions to occur. Three of the eight species able to survive the 0ºC water were NIS with cosmopolitan ranges reflecting their broad tolerance limits (*Mytilus galloprovincialis, Crassostrea gigas* and *Ciona intestinalis*). Although such species represent obvious concern for introductions into high latitude ecosystems, it is of note that other species not generally considered as high risk were also able to survive this temperature transition. In particular a polychaete from the family Polynoidae (*Harmothoe waahli*) and the barnacle *Balanus variegates* were able to survive in all temperature preparations from 0ºC through to 25ºC. Such species obviously pose a high risk of introduction to a wide range of environments including Antarctica and the sub-Antarctic islands.

A severe deterioration of the water quality in the tanks replicating a voyage from temperate to subtropical water is indicative of high stress and advanced decay of dead individuals. The large ascidian *Pyura stolonifera* underwent 100% mortality and the subsequent influx of decomposition products is largely responsible for the observed water quality drop. This change in water chemistry is likely to have adversely affected other organisms in the tanks and accelerated any stresses caused by the temperature increase. Although it is not possible to separate the ultimate stresses caused by water quality and temperature at 25ºC, it is important to note that an average of 48% of species that were able to survive the duration of the experiment at the elevated temperature were NIS. While some native species were able to survive at these temperatures, the surviving assemblages were dominated by individuals of the introduced molluscs *Crassostrea gigas* and *Mytilus galloprovincialis* and the introduced crustaceans *Halicarcinus innominatus* and *Petrolisthes elongatus*.

The current approach provides a rapid and effective method to quickly assess the pool of potential invaders to a new region. While previous approaches have focused upon detailed tolerance data obtained for key invasive species (Hayes & Hewitt, 2000a), these data are not available for the majority of species. Temperate ports around the world share similar habitat characteristics and thus a similar pool of invasive species, yet the coastline of the sub-Antarctic islands and Antarctica represent substantially different environments. It is likely that an approach focusing on key invasive species from temperate regions would overlook important species that, although non-invasive in mid-latitude regions, could prove to be substantial pests in high-latitude environments. Additionally, this approach provides a means of comparing the relative survival of temperate communities transported to both warmer and cooler environments.

Conclusions

As rates of visitation to Antarctica and the sub-Antarctic islands continue to accelerate, the threat of human mediated marine introductions will also increase. This investigation identifies high risk species that typically recruit to fouling communities within temperate ports, and which can subsequently survive transport to a variety of destination along a latitudinal gradient. Transport to the sub-Antarctic islands represents the greatest risk, with 30 species surviving the change in water temperature from 13ºC to 5ºC. Although assemblages exposed to Antarctic temperatures only supported 8 species by the end of the trial, the presence of known invasive species surviving at 0ºC demonstrates that even these extreme temperatures are not sufficient to exclude common marine pests present in temperate ports.

The dominance of NIS in tanks exposed to thermal change reflects the broad tolerance of successful NIS to changes in ambient water conditions. This eurythermal behaviour is likely to have played a major role in the success of such species in establishing non-indigenous populations. Notably, some native species not known to have invasive characteristics also possessed very broad tolerance levels and were able to survive changes in water temperature from 25ºC through to 0ºC. Such species obviously pose a considerable threat of being overlooked in management and surveillance measures that focus only upon known pest species from temperate ports.

A few circumstances exist in which entire communities may achieve transport and be introduced directly into the sub-Antarctic or Antarctic environment – historical shipwrecks abound in these regions and the recently reported instance of a barge being transported to Macquarie Island (Chapter 4 herein; Lewis *et al.*, 2006) demonstrates modern pathways for the direct and potentially permanent introduction of non-indigenous communities. In the majority of instances however a species achieving viable transport is insufficient to result in an established introduction without a reproductive event or the physical liberation of viable individuals from the fouled surface. This study makes no attempt to address the possibility of these events occurring however observations of spawning behaviour provide some insight into this process. Successful reproduction occurred in three NIS (*Petrolisthes elongatus, Halicarcinus innominatus, Mytilus galloprovincialis*) maintained at sub-Antarctic temperatures and also in the mussel *Mytilus galloprovincialis* within the Antarctic temperature aquariums. While stress is often a causal mechanisms in the spawning of marine invertebrates (Apte *et al.*, 2000), larvae were observed to survive in the aquariums for extended periods and larvae of *M. galloprovincialis* successfully settled and attached to the glass of the aquariums. In addition to the continued survival of adult individuals, these observations suggest that these species possess the means of liberation and establishment within high latitude environments.

Section IV

Risk Assessment

Chapter 7: Risk Assessment

Assessing the risks of invasion by marine pests at Macquarie Island

Published as: Lewis PN & Summerson, R. (2006). Assessing the risk of invasion by marine pests at Macquarie Island. Report to the Department of Environment and Heritage. 35pp.

Abstract

This report assesses the risks of introduction of non-indigenous marine species to the Macquarie Island Marine Park. Macquarie Island is located approximately 1500 km south-east of Tasmania and is a part of that state. The Australian Antarctic Division has operated a research station on the island since 1948 and this represents one of the two main focuses of shipping traffic, the other being tourism voyages. The opening of the Macquarie Island Toothfish fishery in the mid-1990s resulted in a single vessel being licenced to fish. Under the terms of the 2006 fishery management plan, up to three vessels will be permitted to fish in the future. Most vessels approaching the island do so from Hobart, either direct or via Antarctica, or alternatively from a number of ports in southern New Zealand. All of the ports from which vessels regularly operate are known to be infected with invasive marine species. The Macquarie Island Marine Park was proclaimed in 1999 and comprises two Habitat/Species Management Zones and a Highly Protected Zone in Commonwealth waters to the east and south of the island.

Analysis of environmental tolerances show that at least seven species of introduced marine pests, resident in ports in Australia and New Zealand, could potentially survive and complete their life cycles in the water temperatures that are found at Macquarie Island. There are, however, other factors which limit or prevent a NIS from becoming established and, in the case of Macquarie Island, the high wave energy environment probably plays an important role.

The focus of shipping activity is inevitably the island and adjacent waters and the shallow water areas provide the most suitable habitat for the establishment of coastal NIS.

This region is predominantly outside the marine park, though there are small areas of shallow water within the Highly Protected Zone of the Marine Park. It is the shallow water areas near the island that are at greatest risk from a marine pest introduction and, if action is not taken, a pest may extend its range into the Marine Park, though it is likely to be restricted to the shallow water areas of the Marine Park (see Figure 7.3).

A risk assessment has been undertaken of the seven groups of vessels or vectors to the island. The vector groups are:

- Research vessels
- ANARE watercraft
- Other research and re-supply vessels
- Fishing vessels
- Tourism vessels
- Cruising yachts
- Natural and anthropogenic debris

All vectors present an element of risk but entrainment risks escalate rapidly when vessels spend long periods in ports infested with non-indigenous marine species. All of the regular ports of departure for Macquarie Island are infested with one or more pest species. Vessels travelling relatively short distances from these ports direct to the island at speeds slow enough not to exert strong sheer forces represent a major translocation risk. The risk assessment section of the report includes proposed management measures to minimize the risks of translocating marine pests to the island. Finally, the recommendations include conducting a baseline survey to determine that no invasive species has already taken hold. A program of education and awareness-raising is also proposed for TASPAWS Rangers to look out for unusual marine organisms as part of their duties on the island.

Introduction

Background: invasive marine species in the subantarctic islands

Introduced marine species have engendered concern for coastal ecosystems throughout the world and are recognized as a major component of global change (Occhipinti-Ambrogi & Savini, 2003). NIS (NIS) have been reported from marine environments of all continents including Antarctica (Tavares & Melo, 2004), and invasive populations that possess the ability to aggressively spread their range and impact upon native community dynamics are considered one of the primary threats to coastal biodiversity (Carlton, 2001; Lubchenco *et al.*, 2001; Hewitt, 2003). Studies into the impacts of NIS have focused upon highly modified port regions where transport vectors associated with shipping serve to deliver a diverse number of potential invaders and where a highly modified environment, the presence of pollutants and a high degree of similarity in the environmental parameters of harbour regions throughout the world result in a high rate of establishment for invasive organisms (Hewitt *et al.*, 1999). Despite this focus it is becoming clear that the problem is not contained within these areas and that NIS are capable of establishment in environments considered as unmodified and comprising high conservation values (Wasson *et al.*, 2001; Orensanz *et al.*, 2002; Wyatt *et al.*, 2005).

Many regions that are recognized for their natural values and are awarded protection status through marine reserves may already be highly modified by the influence of exotic species (Carlton, 1989). Due to the biodiversity values inherent in such ecosystems, the impacts associated with NIS in marine reserves are likely to be of a greater magnitude than impacts typical of highly invaded port regions where a long history of human activity has often dramatically altered the natural state of the environment. Introduced species have been identified as a significant component of the fauna and flora in several marine reserves and also within some World Heritage areas (Simberloff, 2000; Wyatt *et al.*, 2005). In remote high-conservation value locations such as the sub-Antarctic islands, the absence or low level of typical environmental stressors such as pollution, over-fishing and coastal modifications means that in conjunction with global climate change, the establishment and spread of invasive species represents the most profound threat to the biological integrity of these environments.

Macquarie Island is one of two Australian sub-Antarctic island groups[4] and represents a region of significant natural and geological value. Although the isolation of this island has ensured a relatively low rate of visits, humans have had a conspicuous presence on Macquarie Island for nearly 200 years. The absence of suitable harbours has prevented the substantial modification of the island's coastal zone; however the establishment of a research station and the island's attractiveness as a tourist destination has increased the rate of visits and raised the risks of human impacts.

Macquarie Island's seals and penguins were heavily exploited during the nineteenth and early 20th centuries. It was made a wildlife sanctuary in 1933, though by then exploitation had come to an end. The populations of seals are still recovering from near-extinction. In the years since the establishment of the nature reserve and the advent of the ANARE station in 1948), there have been no major impacts from human activities on the island's marine ecosystem with the potential exception of the fishery. Studies of the impacts resulting from a 270 000L oil spill following with the grounding of the *Nella Dan* in 1987 have shown no significant long-term impact in the communities of kelp hold-fasts (Smith & Simpson, 1995). Similarly, studies of human effluent discharge sites have suggested that the anthropogenic input of nutrients has no significant effect on adjacent communities which are also regularly exposed to high nutrient levels originating from Macquarie Island's prolific wildlife (Smith, 2000). The low level of impacts in the marine ecosystem is in stark contrast to the terrestrial environment where feral populations of birds, mammals, insects and plants have significantly modified the natural state of the environment.

Very little is known regarding the rate of marine introductions in the Southern Ocean islands. Early records of the blue mussel *Mytilus edulis*[5] (Ralph *et al.*, 1976) and several species of cosmopolitan algae (*Acrosiphonia arcta, Enteromorpha compressa, Enteromorpha intestinalis, Petalona fascia, Scytosiphon simplicissinus, Porphyra sp.* in Clayton *et al.*, 1997) suggest that human transport does result in the introduction of marine species. As with modern observations of the spider crab *Hyas araneus* (Tavares & Melo, 2004) and anomuran and brachyuran larvae (Thajte & Fuentes, 2003) however, introduced species in Antarctica have only ever been recorded on one occasion and in one life-history stage (Barnes *et al.*, 2006) and it is unknown but doubtful that these

[4] The other sub-Antarctic island group is Heard Island and McDonald Islands.
[5] It is likely that this record relates to *M. galloprovincialis*. See Chapter 5.

populations have persisted. The only published report of marine introductions in the Pacific sector of the Southern Ocean were presented in a report by Cranfield *et al.* (1998) which lists several introduced marine pests from the New Zealand sub-Antarctic group. The extent to which the Macquarie Island marine ecosystems are affected by non-indigenous marine introductions is still unknown.

The introduction of invasive marine species represents a profound hazard to the marine ecosystem of Macquarie Island. While petroleum and effluent discharges can have devastating impacts and persist for some time, an established NIS population is potentially able to expand its population and subsequently increase its density and range. Shipping traffic to Macquarie Island is relatively low, however all visiting vessels have the potential for introducing marine and also terrestrial pests to the island. This is demonstrated by the 37 species of introduced plants and animals that have become established in terrestrial habitats of Macquarie Island, some impacting heavily on native communities (Frenot *et al.*, 2005). As the island has no suitable area for landing fixed-wing aircraft, shipping will continue to be the major mode of transport to this area, resulting in the continual operation of an obvious transport pathway for non-indigenous marine organisms. Given the consistent and accelerating rate of shipping traffic to the island associated with science and tourism operators, DEH has identified that the potential for the introduction of marine organisms may represent a significant risk to the conservation values of the Macquarie Island Marine Reserve and adjacent waters.

Project scope and objectives

The objective of this report is to undertake an ecological risk assessment into the risks of introduction, by human means, of alien marine organisms that may pose a threat to the natural plant and animal life and benthic communities of the Commonwealth Macquarie Island Marine Park, and to the waters encompassed by the Macquarie Island Nature Reserve which comprises State waters, i.e. those waters within three nautical miles of the island (including Bishop and Clerk and Judge and Clerk Islets). Key objectives of the project include:

1. Undertake a literature review relating to marine pests and sub-Antarctic islands;
2. Analyse characteristics and patterns of movement of vessels arriving at Macquarie Island (MI);

3. Review potential invasive species, their life histories and their potential for being translocated to MI and becoming established;

4. Review the MI marine environment with regards to the likelihood of marine pest establishment. This should include temperature tolerances, trophic niches, and availability of suitable substrate for invasive organisms;

5. Prepare a risk assessment for all likely vectors of marine pests. This should be in two parts: a risk assessment methodology and the risk assessment itself.

6. Recommendations for management actions, including education and communication needs; and

7. Recommendations for further research and monitoring.

Description of Macquarie Island

Location, conservation status and regional context

Macquarie Island lies in the Southern Ocean approximately 1500 km SSE of Tasmania in the vicinity of longitude 158°55'E, latitude 54°30'S (see Figure 7.1). The island represents the exposed crest of the Macquarie Ridge and is recognized as the world's only outcrop of oceanic crust uplifted above sea-level, the primary factor contributing to its world heritage listing. Macquarie Island is approximately 34 kilometres long and up to five kilometres wide (TASPAWS, 2003). Eleven kilometres to the north of the island lie the Judge and Clerk Islets, and the Bishop and Clerk Islets are located approximately 37 kilometres to the south of the southern end. Together these islands represent the only terrestrial environments in the Macquarie Island Region ("the Region"). The Region covers an area of approximately 47.6 million hectares and extends 200 nautical miles out from Macquarie Island and the northern (Judge and Clerk) and southern (Bishop and Clerk) islets (Environment Australia, 2001). The Region therefore comprises that part of the Australian Exclusive Economic Zone delineated about Macquarie Island, see Figure 7.1. The north-eastern portion of the Region is truncated where it abuts the New Zealand waters surrounding Campbell and Auckland Islands.

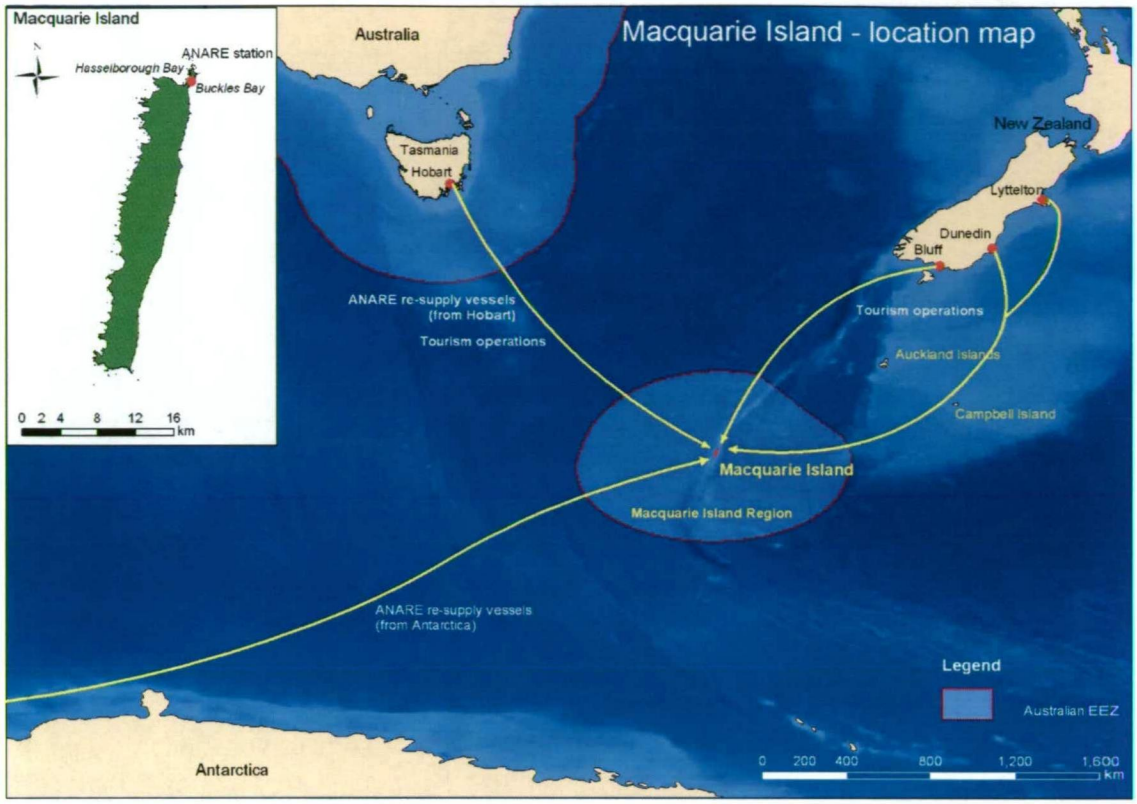


Figure 7.1: Map showing location of Macquarie Island and routes taken by principal vectors. (Data sources: Geoscience Australia, Australian Antarctic Division and National Oceanic and Atmospheric Administration (NOAA)).

The Macquarie Island marine flora and fauna forms a biogeographical continuum with the New Zealand sub-Antarctic islands and shares a large component of its biological assemblage with the islands of the Campbell Plateau. Dispersal has occurred between these islands over long timescales in association with natural flotsam such as kelp rafts, deep water dispersal associated with the Macquarie Ridge and possibly through the advection of larvae (Knox & Lowry, 1977; Helmuth *et al.* 1994). The modern operation of a common vessel pathway associated with the tourism industry and science in this region creates a new, rapid dispersal mechanism operating over an unnatural timescale. These regions are receiving increasing rates of visit and it has been demonstrated that visiting vessel traffic can carry a highly diverse assemblage of associated marine organisms (Lewis *et al.*, 2003; 2005a), and that these species are capable of surviving voyages to even the most remote high latitude islands (Lewis *et al.*, 2004; 2005b).

The unique biodiversity and wilderness value of Australia's Macquarie Island is recognized through several conservation regimes ranging from state and national measures such as Nature

Reserve (Nature Conservation Act 2002) and Marine Reserve status (Environment Protection and Biodiversity Conservation Act 1999), through to international measures such as UNESCO Biosphere Reserve and World Heritage Area designation.

History of human visits and uses

Macquarie Island was discovered in 1810 by Captain Frederick Hasselborough aboard the sealing brig *Perseverance* and was named after the then Governor of New South Wales, Lachlan Macquarie. This discovery was made during extensive explorations aimed at locating new islands that boasted commercially viable populations of fur seals. The motive for the discovery of Macquarie Island ensured that the large-scale harvest of the fur seal populations at Macquarie Island ensued immediately upon its discovery and within a very short period the seal population was under severe pressure of over-exploitation. This period of wildlife exploitation lasted until 1919 and included two peaks of activity corresponding to the harvest of fur seals for skins, and then the harvest of elephant seals and penguins for oil. The fur seal industry failed following the commercial extinction of the target resources, and the seal and penguin oil industry eventually became uneconomic, but during the peak of this period Macquarie Island was visited by up to 15 vessels a year (Lewis *et al.*, 2005). This era left a legacy in the form of a number of established shore stations representing some of the earliest industrial sites in Australia, as well as over eleven vessels wrecked along the island's rugged coastline (Nash, 2003). As a consequence of this activity, and also noting that a number of vessels had been wrecked on the island before Hasselborough reported its presence, it should not be surprising if non-indigenous marine species have already been introduced to the marine environment surrounding the island, transported on the hulls of these wooden vessels.

The detailed record of shipping visits to Macquarie Island offers a rare opportunity to examine the exact rate at which transport pathways for NIS have operated since the first vessel landed. The two peaks associated with the harvest of fur and oil are clearly evident in the records of ships visiting the island. The harvest of fur seals reached a peak during the period 1810-1840 whilst the exploitation of elephant seals and penguins peaked during the period 1875-1920 (see Figure 7.2). A final, larger, peak associated with the Australian National Antarctic Research Expeditions (ANARE) scientific exploration, and with the growing tourism industry, is obvious over the

period 1971–present. This recent peak is likely to continue to rise as tourism in the Region develops (Frenot *et al.* 2004). Even though ship traffic has increased significantly in recent years, and presently ranges between 9 and 15 visits per year, it is still low compared to mainland ports. For example, Port Phillip Bay currently receives over 3000 visits per year (Joanne Weinert, AQIS, personal communication, 2004). From shipping records, it can be estimated that the total number of ship visits to Macquarie Island since its discovery is only 450-460 (Figure 7.2).

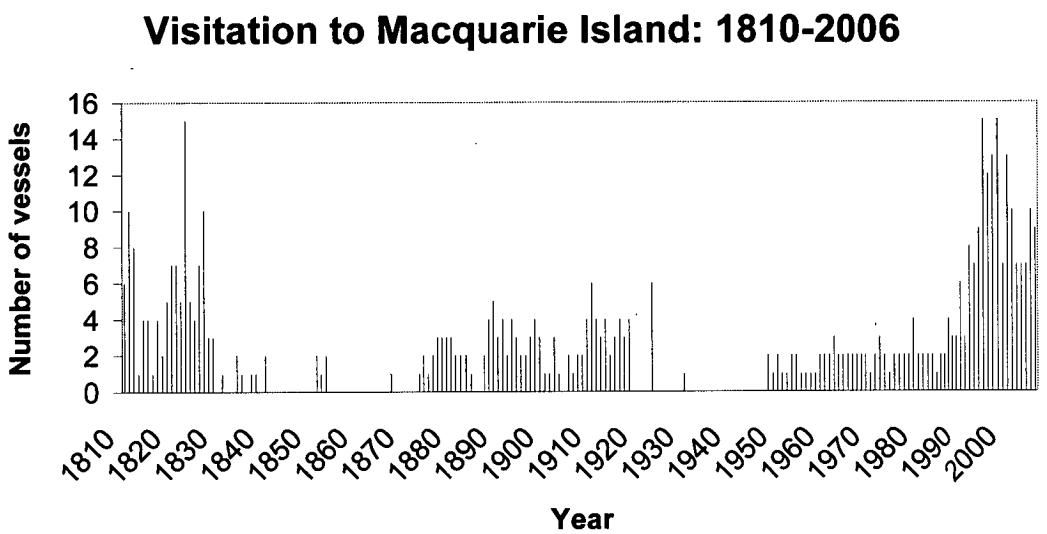


Figure 7.2: Ship visits to Macquarie Island since its discovery in 1810. Three peaks of visitation are clearly discernable and relate to the harvest of fur seals for the fur trade (1810-1840), the oil trade targeting elephant seals and penguins (1880-1920), and the modern era (1971 – present). Vessel traffic records were extracted from Cumpston (1968) and from ANARE historical visit records.

Marine and coastal habitats

The Macquarie Island Marine Park encompasses a variety of large-scale benthic habitats, each exposed to different depths, currents, nutrient levels, wave activity and temperatures (Butler *et al.*, 2000; Robinson and Scott, 1999). The primary habitats at risk from marine introductions are shallow in-shore environments; no NIS have been detected in water depths below 200 m. In shallow locations the biological, physical and chemical conditions most closely resemble those found in the donor regions which may host potential NIS that are able to be translocated by transport vectors. While the marine park encompasses a large area of deep oceanic ridge and abyssal plain, (see Figure 7.3b) the assessment of risk for introductions is specifically focused upon in-shore communities. In the event of an introduction of a NIS, it is these areas that are

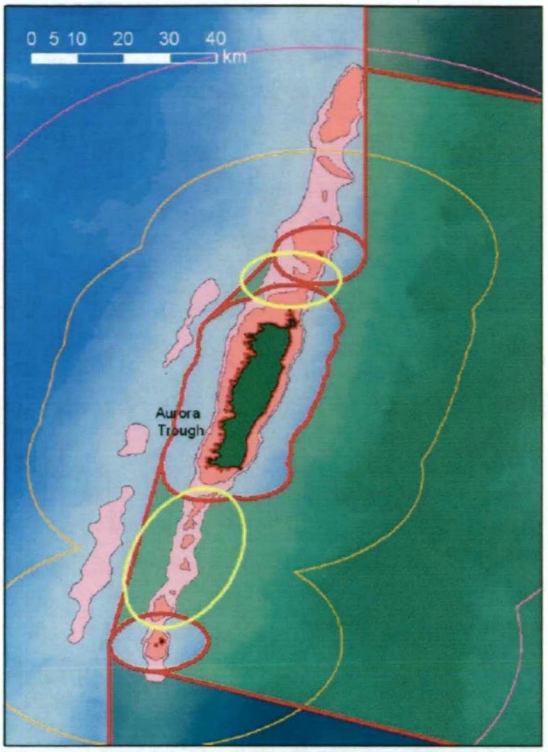
most at risk, though there are many other factors in addition to water depth that may influence the dispersal of an invasive organism. Figure 7.3a shows the areas where the water depth is shallower than 200m. The areas circled in yellow are shallow water areas within the highly protected zone of the marine park. These areas combined comprise approximately 167 km^2 and represent approximately 0.15% of the total area of the highly protected zone.

Macquarie Island has an exposed, high wave energy coastline with no large sheltered bays, harbours or estuaries. The western side of the island is rugged and exposed and consists of numerous small bays and a raised marine terrace with relict sea-stacks and a prominent coastal terrace in the northern section (TASPAWS, 2003). The eastern side of the island is more sheltered from the dominant weather patterns, however it is still prone to regular storms and the associated high seas and strong winds. The eastern coastline has sand and shingle beaches and occasional rock platforms. The tidal range experienced on the island is from 0.5 to 1.5m. The high wave action in combination with strong prevailing winds and a constant high humidity have resulted in an extended inter-tidal zone. Below this zone the predominant substrate is rocky reef or coarse volcanic shingle.

The inter-tidal region of Macquarie Island can be described by six distinct zones (Kenny & Haysom, 1962, Simpson, 1976; Smith & Simpson, 2002). These zones include (from top to bottom):

- a transition zone dominated by lichen;
- a broad zone dominated by the macroalgae *Porphyra*
- a bare zone heavily grazed by gastropod molluscs;
- a conspicuous kelp zone characterized by the large macroalgae *Durvillea antarctica*; and
- the lower red algae zone that supports a variety of Rhodophyte species.

The shallow sub-tidal environment is characterised by the brown alga *Macrocystis pyrifera* and an undercanopy of various macroalgae (see Ricker, 1987). Although the invertebrate fauna is not as diverse as temperate regions, the shallow sub-tidal community includes a number of conspicuous species and represents a distinct example of a sub-Antarctic marine assemblage (Kenny & Haysome, 1962; Smith & Simpson, 2002).



Legend

Areas of shallow water

-100m

-200m

Jurisdictional boundaries

3nm

12nm

24nm

Limit of EEZ

Marine park boundaries

Highly Protected Zone

Species/Habitat Management Zone (North)

Species/Habitat Management Zone (South)

Marine Park boundary

Note: The Marine Park boundary around the islands is at 3 NM from the coast and represents the limit of Tasmanian coastal waters.

Areas potentially at risk

Figure 3a (left). Shallow water areas around Macquarie Island

Figure 3b (below). Extent of the Macquarie Island Marine Park

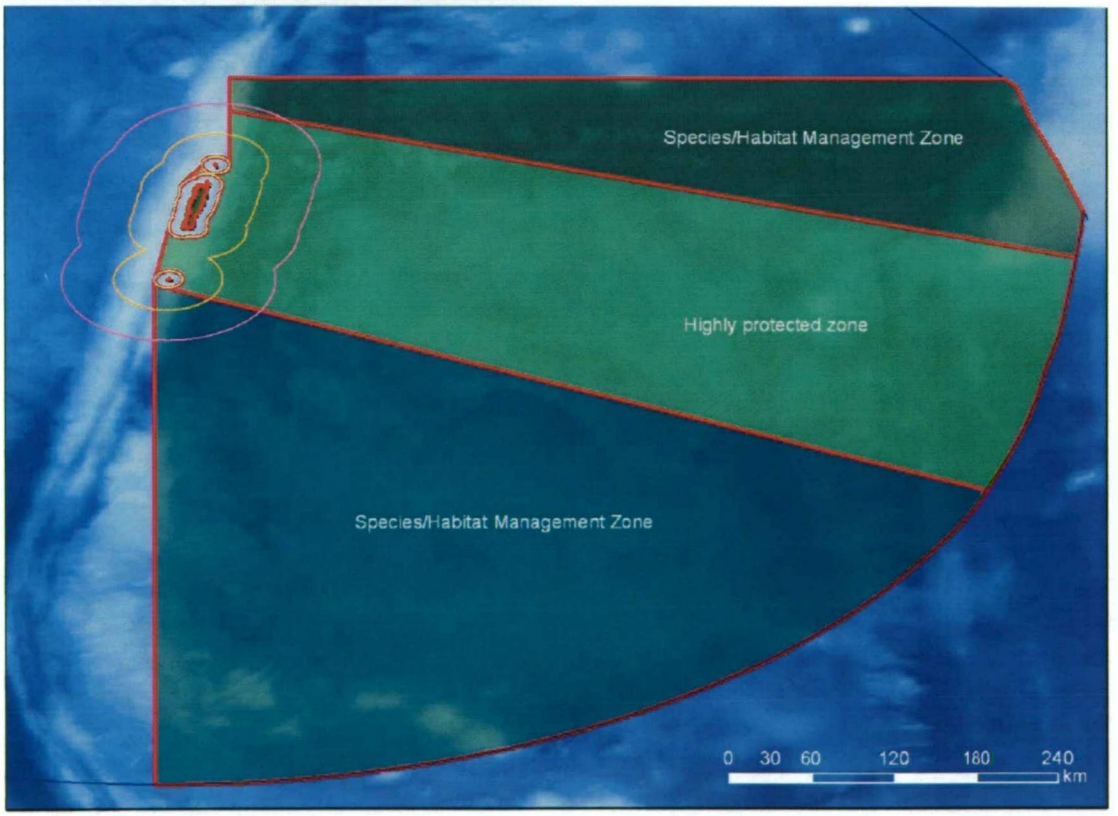


Figure 7.3. Extent of the Macquarie Island Marine Park and shallow water areas around the island. (Data sources: Australian Antarctic Division. Department of the Environment and Heritage).

Owing to its maritime influence and its high latitude location, Macquarie Island experiences stable water temperatures that fluctuate between 2ºC and 7ºC. This is one of the most significant factors limiting the potential for species from more temperate environments from establishing in Macquarie Island's coastal environment. Figure 7.4 shows the range of temperature experienced in the island, the Bruny bioregion (which includes Hobart) and Antarctica. Although the temperatures of Macquarie Island do not overlap those of the other ports at any time of the year, most species have thermal tolerances well beyond the bounds of their native range and the extent of the difference is unlikely to exclude many groups.

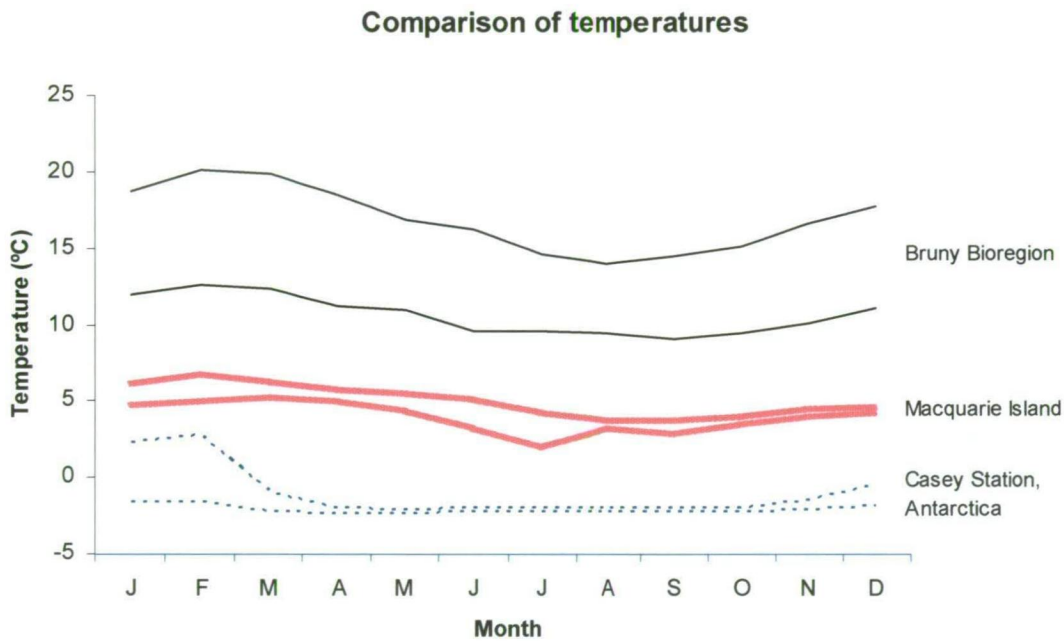


Figure 7.4: Water temperature ranges of the Bruny Bioregion (which includes Hobart), Macquarie Island and Antarctica showing the large difference in the extreme temperatures between donor regions and Macquarie Island. Data supplied by NTF. (Water temperature data from New Zealand not available.)

The absence of sheltered harbours and bays may be a more limiting factor than the simple difference in temperature between Macquarie Island and the donor ports. The similarity in port environments throughout the world has been cited as a significant factor in the spread of invasive species (Ruiz *et al*, 1999), and most invasive species are well adapted for survival in such habitats. Thus the absence of sheltered harbours results in an environment that is unlikely to suit the requirements of most invasive organisms. This feature of the coastline also serves to limit the

potential for ships to deliver species due to the inability of vessels to approach in-shore, the limitation on safe anchorage time and the lessened duration of stay. Although the typical contingent of invasive species may be limited by the exposed, high-energy coastlines, other species that may not be considered invasive in the donor regions may find a suitable habitat at Macquarie Island. An assessment of target pests should take into account the ability of pest species to survive in exposed coastlines as well as typical port environments.

Low biodiversity is suggested to result in a high risk of introduction due to the presence of open niches that may allow introduced species to establish a "toe-hold" in the new environment. As with other islands of the Southern Ocean, Macquarie Island is notable for its overall low biological diversity, but high numbers of some species (EA, 2001). In addition to this low diversity there exist some conspicuously absent trophic guilds such as littoral mussels and many fish groups. In the instance of mussels, the Mytilid *Mytilus galloprovincialis* is present in, and native to[6], the New Zealand sub-Antarctic islands and also on the Kerguelen Island at a higher latitude than Macquarie Island, suggesting the latter falls within the suitable range of this species. Invasive populations of this species have caused extensive change to coastal communities in South Africa including the displacement of indigenous species and a dramatic increase in inter-tidal mussel biomass (Robinson *et al*, 2005).

The isolation of Macquarie Island raises some specific concerns over the conservation of marine communities. Although it is generally perceived that marine organisms are less vulnerable to extinction than terrestrial species, this resilience is primarily attributed to the large range and high dispersal capacity of marine organisms (Roberts & Hawkins, 1999). Local extinctions in the marine environment are possible; however recruitment from adjacent regions usually serves to re-seed the depleted species following over-fishing or other human impacts. The absence of adjacent populations in island ecosystems may make insular marine populations more vulnerable to extinction in a similar fashion to insular terrestrial communities. In many cases, the paucity of knowledge pertaining to marine species may serve to mask the decline and extinction of populations (Edgar *et al.*, 2005). This is a particular concern for the Macquarie Island Region where there have been very few studies of the inshore marine ecosystem and where no base-line survey of the littoral fauna has been conducted. Scott (1994), for example, compiled a list of all

[6] The taxonomy of *Mytilus galloprovincialis* is complex as there are several different strains. See Chapter 5.

known benthic invertebrate species from a number of sources but emphasised that the list was incomplete. Whilst it is well known that terrestrial insular environments are subject to rapid extinction events following the introduction of alien species, currently no studies have examined the vulnerability of remote marine environments to invasion. It should be noted, however, that a preliminary survey by CSIRO in 2000 (Butler *et al.*, 2000) found that few of the more than 100 species of benthic fauna sampled were endemic to Macquarie Island. The shallowest samples taken were from Aurora Trough at depths between 200 – 500m and on the eastern side of the island at 200 - 400m depth. This survey was conducted in relatively deep water and may not be representative of shallow water, inshore ecosystems.

Transport Pathways

The global dissemination of marine NIS has been primarily linked to shipping operations, mariculture and deliberate introductions, and also introductions associated with cargo or shipping materials. More recently concerns have been raised that the increasing quantities of floating plastic litter in the oceans is providing an additional pathway for the dispersal of coastal organisms across oceanic bodies (Barnes, 2002; Barnes, 2005).

The relative importance of these pathways varies throughout the world according to the importance of different human activities in any region. Mariculture has been the primary route for the introduction of NIS to some regions and has contributed 31% of introduced species to Britain (Eno *et al.*, 1997). Up to 40% of introductions in Tasmania have characteristics that suggest introduction through this pathway (Thresher, 1999). The deliberate introduction of salmonids to some sub-Antarctic islands has resulted in the establishment of anadromous[7] populations in the Kerguelen Islands which persist to the current day and may impact upon coastal marine communities (Davaine & Baell, 1992). Macquarie Island has not received any deliberate introduction of aquatic organisms, and stringent regulations prevent future deliberate introductions of any species. As a result, this transport pathway, that of deliberate introductions, has not been considered in this report which addresses the accidental introduction of marine NIS to Macquarie Island.

[7] Fish that require freshwater to spawn and reproduce.

Operator classes at Macquarie Island

The only human settlement on Macquarie Island is the ANARE station, which has been in continuous occupation since 1948. Until recently most traffic to the island was confined to research and re-supply voyages operated by ANARE. As a consequence, opportunities for marine introductions have been largely reliant upon only a very small traffic of human visitors. In recent years, however, traffic has also included ship-based tourism, fishing vessels and the occasional cruising yacht[8]. The absence of port facilities and the high wave energy coastlines of the island limit access to much of the island and large vessels generally do not approach the shoreline closer than a few hundred metres and there are no shore facilities such as a wharf or jetty. Access and re-supply activities are reliant upon helicopters or small vessels such as Inflatable Rubber Boats (IRB) and Lighter Amphibious Resupply Cargo vessels (LARC) to transport goods and personnel to shore. Transport opportunities for NIS are limited by the low level of traffic (~14-15 vessels per year) and the short duration of visits. Despite these limiting factors, modern activities do carry an intrinsic risk of marine introductions and it has been demonstrated that Southern Ocean vessels visiting Macquarie Island are capable of carrying diverse assemblages of marine organisms from temperate ports to the Southern Ocean (Lewis *et al.*, 2005).

The vessel type or its operational purpose has been used successfully as a means of grouping specific voyages into categories that reflect the relative risk of introduction (Kinloch *et al*, 2003; Floerl & Inglis, 2005). Visits to the Macquarie Island Region can be attributed to tourism, science and fisheries activity. In the past two decades 60.8% of traffic has resulted from tourism activities, 27.2% has resulted from science activities and 12% of traffic has been the vessel licenced to fish the Region (see Figure 7.5). Due to the differing objectives of these operators, the hazards for marine introduction varies and risks are therefore assessed separately for each operator type, see discussions and conclusions.

[8] International vessels occasionally pass through the Region. Analysis of AMSA Australian Ship Reporting System (AUSREP) data from 1999 – 2005 revealed that a Japanese research vessel reported once from the Region during 2002 and again in 2004 and a US tanker reported during 2003.

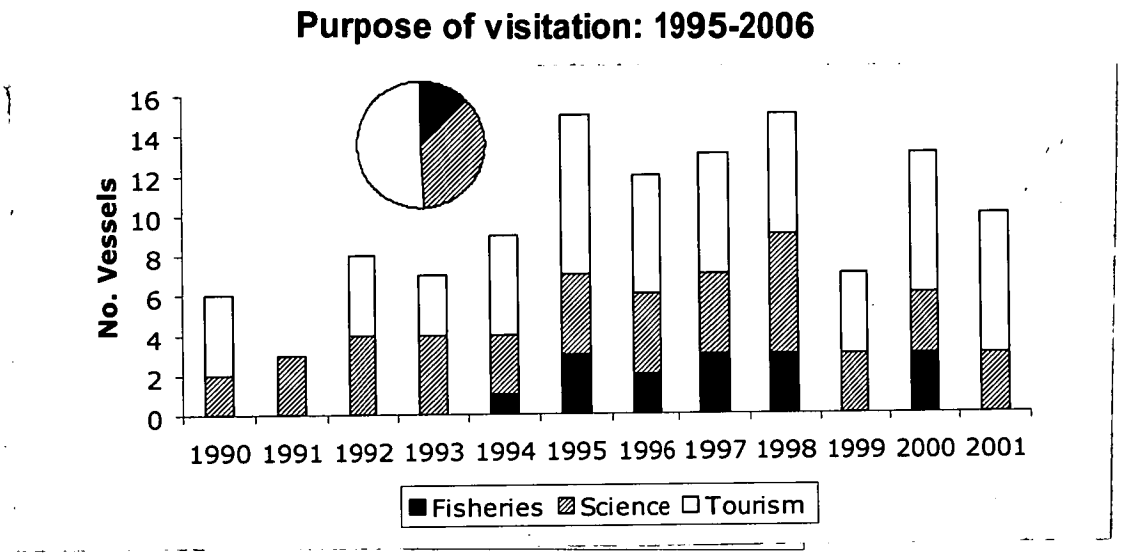


Figure 7.5: Purpose of vessels visiting Macquarie Island in the period 1990-2006. The pie graph displays total visit proportions for this period and indicates that tourism provides the bulk of traffic.

Tourism

Tourism is a growing industry in the Southern Ocean region and currently contributes the highest portion of traffic to Macquarie Island (~ 60%). Although several operators facilitate tourism ventures to the Region, transport is primarily dependant on three vessels: *Akademic Shokalskyi* , *Kapitan Khlebnikov* and *Spirit of Enderby*. All are ice class 1A vessels that also visit the Antarctic continent and the New Zealand sub-Antarctic islands and are Russian owned and operated icebreakers or oceanographic research vessels. Tourism ventures usually visit Macquarie Island either as part of a trip to Antarctica or as a smaller trip focusing on the New Zealand sub-Antarctic islands and Macquarie Island. Visits typically follow a path from Hobart directly to Macquarie Island then either to the Ross Sea region or to the New Zealand sub-Antarctic islands and finally to a port in New Zealand, usually either Bluff, Lyttelton or Dunedin. Upon completion, the vessel will often retrace the same voyage in the opposite direction and continue to do so for the duration of the austral summer. Tourism vessels may spend up to five days in the Region.

In addition to visits by larger tourism operators there have been some records of visits by private yachts. Floerl *et al.*, (2005) have demonstrated the potential for small recreational yachts to facilitate the transport of marine communities and have suggested that that this is a major avenue for the introduction of exotic species to New Zealand. Lewis *et al.*, (2005) have shown that even a well maintained yacht visiting the Auckland Island group can carry small communities of invasive organisms that can readily detach from the hull surface. In the instance of the yacht *Tiama*, communities of up to three species were found on flaking paint fragments that were easily detached from the vessel into the sub-Antarctic environment. Although yachts must comply with the same visit guidelines as tourist vessels and must anchor at least 200m offshore to the closest point of their anchor swing, the ability of such vessels to approach close to the coast and anchor in shallow water make this a potentially high risk pathway.

Science activities

The ANARE research station at Macquarie Island is supported by the Australian Antarctic Division and transport of research expeditioners relies upon re-supply vessels such as *Aurora Australis* and *Polar Bird*. Scientific re-supply vessels contribute ~ 27% of the total traffic and generally either travel directly to Macquarie Island from Hobart and then continue to the Antarctic continent before returning to Australia or follow the reverse route. In past years there has been at least one dedicated, round-trip voyage to the island per year. The station is located on the isthmus at the northern end of the island (see Figure 7.1, inset). Resupply operations are preferentially carried out from Buckles Bay, on the eastern side of the island, or Hasselborough Bay, on the western side, if the weather requires it (see Figure 7.1, inset). Vessels often spend three or more days in the vicinity of the island, sometimes anchoring in Buckles Bay if the weather is calm.

A recent shift of focus by the Australian Antarctic Division has resulted in the removal of some station resources and a reduction of logistic support for transport to Macquarie Island. This has resulted in a greater reliance upon tourism vessels as the primary mode of transport to the island.

Research in the Macquarie Island Marine Park is subject to the granting of a permit by the Commonwealth Department of the Environment and Heritage. Two such permits have been granted since 2002 (A. Mednis *pers. comm.*)

Fisheries

In the austral summer of 1994-95, a single Australian vessel started exploratory fishing for Patagonian toothfish (*Dissostichus eleginoides*) in the Region under a permit from AFMA. Two main fishing grounds were discovered: Aurora Trough to the west of the island (see Figure 7.3) and along the Macquarie Ridge to the north of the island. *Austral Leader*, the licenced vessel, did not fish every year following the establishment of the fishery and Aurora Trough was closed to fishing between 1999 and 2003. To date, fisheries operations from this vessel have only contributed 12% of visits to the Macquarie Island Region (see Figure 7.5). With one or two very limited exceptions where personnel have been taken off the island by IRB, the fishing vessel has not approached the coast. The vessel is prohibited from fishing within three nautical miles of the coast, which are Tasmanian state waters. Austral Fisheries, the company operating this vessel also fishes in the Heard Island and McDonald Islands Fishery.

Austral Leader has now been retired from fishing and has been replaced with *Southern Champion*. *Southern Champion* is based in Albany and operates almost solely in the Macquarie Island and Heard Island fisheries. The catch of toothfish is most often offloaded at Albany and, rarely, at Mauritius. Austral Fisheries (M. Exel *pers. comm.*) advise that *Southern Champion* does not use ballast water and the hull is cleaned on the slipway and antifouled annually. Hewitt *et al.* (1997) report the presence of *Sabella spallanzanii* in Albany but the risks of translocation by this vessel appear to be minimal, especially as *Sabella* prefers sheltered locations (NIMPIS 2002a).

In an assessment of the risk of commercial fishing vessels spreading marine pests, Summerson and Curran (2005) highlighted potentially high risk activities specific to this and other fisheries vessels operating around Macquarie Island:

- Demersal trawling (risk of entraining invasive organisms)
- Long distance participation (risk of long-distance translocation)
- Risks associated with ballast water management
- Seasonal fishery (risks associated with a vessel spending extended periods in port and accumulating biofouling)

The recommended management actions for this fishery were:

- Ballast water should be managed in accordance with the requirements of the Australian Ballast Water Management Framework, including relevant Australian Government and State/Territory legislation.
- Vessel cleaning and antifoulant performance are critical when vessels fish in pristine waters
- Vessels travelling long distances to participate in a fishery should have clean hulls and their internal waters systems flushed with fresh water before departure.

As *Southern Champion* does not use ballast water and does not fish in mainland fisheries, these particular risks no longer apply. The vessel hull cleaning regime will minimize risks associated with hull fouling.

The recently released (January 2006) Macquarie Island Toothfish Fishery Management Plan 2006 now allows for three vessels to fish in the Region (AFMA 2006). The region has been divided into two sectors: Aurora Trough and along the Macquarie Ridge north and south of the island. Half the statutory fishing rights will be sold following a competitive tender process; the other half will be allocated to Austral Fisheries. The only fishing gear licenced to date are mid-water and demersal trawl nets; longlines have been banned to minimize the risks of hooking interactions with seabirds.

Illegal,Unregulated and Unreported (IUU) fishing has been a widespread problem in the Southern Ocean. There has, to date, been only one suspected incursion by an IUU vessel in the Region. The FV *Taruman*, a Cambodian-flagged longliner, was arrested by the Customs and Fisheries patrol boat *Oceanic Viking* in September 2005 after the vessel was observed by surveillance aircraft inside the Australian EEZ south of the island in June 2005.

Vessels as transport vectors at Macquarie Island

Vessels visiting Macquarie Island can facilitate introductions in a variety of ways. The vessel hull and internal water systems can support viable assemblages of organisms, or the vessel may carry entrained water or equipments that may support biological assemblages. Two primary avenues for introduction in association with a vessel have been considered below.

Ballast water

Ballast water provides a viable route for the introduction of a variety of organisms and has been implicated in a range of established NIS (Hallegraeff & Bolch, 1992; Wonham *et al.*, 2001). Introductions in association with ballast water occur when vessels offload cargo at ports and subsequently draw ocean water into ballast tanks to compensate for the altered weight and to restore the trim of the vessel. This water can contain a large range of planktonic organisms including the larval stages of benthic species. When the vessel moves to a new port and loads new cargo aboard, the ballast water from the last port of call is discharged in the new port and entrained organism that survive the discharge process may be introduced.

The typical pattern of vessel operation at Macquarie Island and in the broader Southern Ocean region reduces the potential for transport of marine species in ballast water. Vessels visiting high latitude coastlines serve a re-supply function and are primarily involved in the offloading of consumable cargo such as fuel and food. As this movement of goods results in the vessel weight being reduced, ballast is not likely to be discharged in the coastal waters of Macquarie Island. High latitude water may be drawn into ballast tanks and transported elsewhere, and it has been observed that Antarctic species of diatoms have been discharged into the Derwent River by the re-supply vessel *Aurora Australis* following ballasting activities around Antarctic sea-ice (Lewis *et al.*, 2003). The typical patterns of ballast activity in the Southern Ocean have been documented by Lewis *et al.* (2005) through an analysis of ballast exchange procedures by all Southern Ocean vessels entering Hobart in the past two decades. It was shown that no ballast was discharged in the coastal region of any Southern Ocean locality including Macquarie Island during this period.

Ballast Water will be controlled in the future by the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 which was developed under the auspices of the International Maritime Organisation. The Convention will enter into force when it has been ratified by member states. In essence, this convention requires ships carrying ballast water to exchange ballast water taken up in port at least 200 nautical miles from land and in water at least 200 metres in depth. This is intended to prevent organisms taken up in ballast water at one port from being transported to another.

Hull Fouling

Hull fouling has been identified as the primary avenue available for the introduction of marine NIS to high latitude regions (Lewis *et al.*, 2005). All external surfaces of a vessel hull are exposed to the marine environment and represent a potential surface for the settlement of epi-benthic species and associated in-faunal communities. Studies of fouling associated with Southern Ocean vessels have demonstrated the rapid accumulation of communities comprising up to 56 species, half of which, in some instances, possessed invasive histories (Lewis *et al.*, 2005). These communities are able to survive a typical voyage to sub-Antarctic islands (the voyage from Hobart to Macquarie Island can take less than three days), with most species arriving at the destination in a viable condition (Lewis *et al.*, 2004). In addition to the ability to settle and survive on hull surfaces, organisms are able to settle in sheltered interstices such as sea-chests[9] and other recessed regions where they are provided with a sheltered means of transport between locations with a high probability of survival (Coutts & Tailor, 2004).

On a global scale it is likely that hull fouling is playing an on-going role in the dispersal of NIS, as well as having been the key mechanism responsible for the historical transport of many marine pests already established in coastal ecosystems. Some features of maritime activities specific to the Southern Ocean, such as the way antifouling applications are used, winter lay-over in ports and typical operating speeds, increase the potential role of vessel fouling as a transport mechanism.

- Antifouling application

Many vessels visiting Macquarie Island also frequently travel to the Antarctic continent and are designed and maintained in a manner suited to transit through sea-ice. Selection of exterior paints for the hulls of such vessels is a trade off between abrasion resistance and the fuel efficiency obtained by using biological retardants that reduce drag caused by fouling organisms. Some vessels such as *Aurora Australis* are treated with abrasion resistant epoxy paints (e.g., Hempadur Multistrength 4575) selected to ensure maximum durability. Such paints contain no bio-retardant agents and are thus subject to settlement by a diverse range of organisms that may pose a hazard of introduction to Macquarie Island. Antifouling paints are used in sheltered

[9] A sea-chest is a cavity in a vessel's hull from which internal water system inlet and outlet pipes lead. It is often protected with a grill fixed flush with the hull.

spaces such as the sea-chests of *Aurora Australis* however the self-polishing nature of these paints is compromised in the low flow-velocity water flows of such spaces and their antifouling capacity is likely to be sub-optimal.

Other vessels such as *L'Astrolabe,* which also overwinters in Hobart docks, use antifouling paint (in this case the tin-based paint Intersmooth BFA954 and BFA956; Lewis *et al.,* 2005). Although such paints may serve to limit the diversity of species settling on the hull, the severe abrasion of the hull during sea-ice transit may compromise the effectiveness of the coating and leave large areas of the hull scraped bare of paint (P. Lewis *pers. obs.*). Even on hulls with newly applied antifouling paint, the application process leaves conspicuous areas of untreated surface corresponding to the blocks upon which the vessel sits during application. These untreated areas (dry-dock support strips) have been shown to support diverse communities and the use of antifouling paint cannot be considered as a single solution to limit the spread of NIS (Taylor & Rigby 2002).

Paint in poor condition can be a particular concern for the introduction of species; marine communities, including several invasive species, have been observed on flaking paint fragments on vessels examined at the sub-Antarctic Auckland Island (Lewis *et al.,* 2005).

- Port layover

Southern Ocean shipping operations are typically inactive during winter periods due to the accumulation of sea-ice which prevents access to the Antarctic continent. Typically tourism vessels travel to the Northern Hemisphere to work in the northern summer and continue to operate on a similar time schedule, though at least one of these vessels (*Kapitan Khlebnikov*) has over-wintered in Tasmania. National science vessels are occasionally leased for other activities during winter but are frequently left in port over the entire winter period. When a vessel is left in port for several months a highly diverse community is able to develop on the hull surface even when antifouling paints have been used. Lewis *et al* (2005) have recorded communities of up to 56 species accumulating on the hulls of Southern Ocean vessels during the winter period. As the vessels are located in highly invaded port environments during this period, e.g. Hobart, a high proportion (up to 50%) of the species that recruit to the hull are either considered invasive or have established non-indigenous populations outside of their native range.

- Speed

Typical speeds maintained by cargo vessels reach in excess of 20 to 25 knots (Carlton, 1992) and result in substantial sheer forces to communities exposed on vessel hull surfaces. Vessel traffic visiting Macquarie Island generally travels at far lower speeds and the *Aurora Australis* has an optimal cruising speed of only 13 knots (P&O Polar, 2001). This lower speed results in far less stress to hull fouling communities, and whilst much fouling is limited to sheltered interstices such as sea-chests on commercial traffic (Coutts & Taylor, 2004), many species are able to survive on the external environment of Southern Ocean shipping. Communities observed on dry-dock support strips on the vessel *Southern Supporter* were examined before and after a voyage to the sub-Antarctic Heard Island and it was shown that at a cruising speed of 12.5 knots, a community comprising 18 species survived the return voyage and a Southern Ocean species of barnacle actually recruited to the community during transit (Lewis *et al.*, 2004). As the voyage to Macquarie Island is shorter than that to Heard Island it is reasonable to assume that the passage to Macquarie Island from ports in New Zealand and Hobart is unlikely to present a significant barrier to the survival of fouling species.

Plastics: A passive anthropogenic pathway to Macquarie Island

The quantity of plastic litter afloat in the world's oceans is rapidly increasing (Barnes, 2005). In addition to representing a hazard of entanglement or ingestion, floating litter provides a durable substrate for the settlement of marine biota and may be capable of transporting species across ocean basins. It has recently been suggested that plastic litter may play a role in the introduction of NIS to Antarctica (Barnes 2002, Barnes & Fraser 2003) and the possibility that NIS could be delivered to Macquarie Island in association with floating plastic must be considered.

Despite the growing concerns over the role of plastic in the dispersal of NIS, several factors specific to the Southern Ocean region limit the potential for this transport mechanism to result in the establishment of new species at Macquarie Island (Lewis *et al.*, 2005).

1. *Plastic litter in the Southern Ocean is generally sourced from mid-ocean fishing activity*

Although plastic litter is conspicuously present along the shore-line of Macquarie Island, this litter is generally dumped at sea by fishing vessels. As the plastic does not spend time in coastal

regions other than Macquarie Island there is no opportunity to accrue a coastal assemblage of organisms that are likely to represent a hazard of introduction to Macquarie Island. Taxa recruited in mid-oceanic environments are likely to be comprised of cosmopolitan species such as gooseneck barnacles that are adapted for transport in association with natural flotsam (e.g. pumice, wood, cetaceans).

2. *Plastic litter is restricted to slow, passive transport in the direction of prevailing oceanic currents*

Organisms that recruit to floating plastics are not provided with a rapid and direct transport pathway to a new region. Transport is restricted to natural current speeds meaning that entrained organisms must survive prolonged periods at sea. Furthermore, prevailing currents in the Southern Ocean dictate a west to east direction of movement which limits the rapid transfer of species between latitudes, limiting the potential transport of species from north to south. Coastal organisms entrained for extended periods on floating plastic are unlikely to survive in nutrient poor oceanic waters for a sufficient time to reach Macquarie Island.

3. *Natural dispersal pathways operate over the same spatial and temporal scale*

The existence of large quantities of floating kelp rafts in the Southern Ocean provides a natural dispersal mechanism capable of providing transport in the same direction and speed as plastic. Kelp rafts are durable and retain a diverse community of organisms associated with their holdfasts (Smith & Simpson, 1995; 2002). Such rafts have been recorded far out to sea, and it is estimated that over 70 million kelp rafts are afloat in the Southern Ocean at any one time (Smith, 2002). Such rafts have been identified as a key dispersal mechanism resulting in the modern distribution of species in the sub-Antarctic region. Although plastics are unlikely to introduce new species to sub-Antarctic locations frequently, it is possible that in conjunction with natural vectors such as kelp, plastics may serve to distribute established NIS between sub-Antarctic islands of similar latitude.

Plastic debris has been the subject of a monitoring project at Sandell Bay on the west coast of Macquarie Island from 1991 to 1994 and 1996 to 2001. (See, for example, Slip & Burton, 1991 and Eriksson & Burton, 2001). Records were kept of marine organisms attached to plastic debris

during 2000-2001. Of the 1192 items recorded, 144 had *Lepas* sp. (gooseneck barnacle) attached and two had species of algae attached. No other organisms were detected.

Driftwood and timber - other potential passive vectors

The marine debris monitoring project at Macquarie Island was restricted to monitoring plastics; timber was excluded to prevent disturbance to any historical sites or shipwrecks (G. Copson, *pers. comm.*). As a consequence, records of driftwood[10] and other timber washed up on the shore are unreliable.

A number of items of driftwood have been found along the shoreline at Macquarie Island. In 1957, a request for samples of driftwood by scientists studying oceanic transport in the Southern Ocean brought 20 specimens (Barber *et al.*, 1959). The authors did not mention whether these had been washed up recently or had been *in situ* for some time. Analysis of the timber showed that eight most likely came from South America, five possibly came from South America and the remainder may have come from as far away as North America. Taking a somewhat arbitrary surface velocity[11] of 25 cm s^{-1} and a geodesic[12] distance of 7,144 km between, say, Ushuaia (54º 47'S, 68º 18'W) in southern Argentina, and Macquarie Island (54º 30'S, 158 º 57'E) it would take at least 330 days for an object to be transported from the southernmost tip of South America to Macquarie Island. No readily accessible records are available on the rate of driftwood transport to Macquarie Island. Geof Copson, who has spent seven years on the island over a 30 year period, observed that "trees did not turn up on Macquarie Island all that often" (G. Copson, *pers. comm.*). Unless a tree or log had spent some time trapped on the shoreline at source, it is unlikely that it would be colonised by littoral species.

Copson (*pers. comm.*) also advised that he had seen construction timber, such as might be used for a jetty washed up on the island. The provenance of such an item is hard to gauge but if

[10] The term driftwood is used here to denote timber derived from natural sources such as trees washed into the sea.

[11] Estimating current velocities over such a large distance is fraught with difficulties and is beyond the scope of this report. This figure is therefore given as a rough estimate but based on a number of calculations. See, for example, Phillips & Rintoul, 2000.

[12] A geodesic route is approximately the same as a "great circle" route and is the shortest distance across the surface of the globe.

driftwood was found to come from South America, that is a possibility in this case also. Alternatives include the French sub-Antarctic stations e.g. Kerguelen, which is the same band of latitude as Macquarie Island and one of the New Zealand sub-Antarctic islands, in which case the timber may have made nearly a full circumnavigation. It seems unlikely that jetty timber would be washed up at Macquarie Island often but it would be worth monitoring all timber arrivals for the presence of attached or encrusting organisms.

Marine equipment

The association of marine communities with items of cargo or packing material has resulted in a number of marine introductions. The operation of this pathway at Macquarie Island has been demonstrated through the transport of a marine community fouling a barge that was moored in the Derwent River for an extended period prior to transport to Macquarie Island (Lewis *et a.l*, 2006). In this instance 20 species including 10 species that have successfully established non-indigenous populations were provided with a transport opportunity to Macquarie Island. Owing to the relatively short (~3 days) transit time to Macquarie Island and the frequent exposure of deck cargo to rain and sea-spray, marine communities are highly likely to survive transport through this pathway. The community on the barge's hull included ~ 136 000 individuals of one invasive species (the amphipod *Monocorophium acherusicum*) and individuals were alive after three days at sea. Not only did this represent a very large founding population; the retention of larvae in brood pouches meant that this species also carried the next generation with it. As the communities associated with cargo are introduced in the new environment directly there is a high risk of successful introduction through transport on cargo and marine equipment.

The transport of scientific and other cargo to Macquarie Island carries an inherent risk for the introduction of NIS to both the terrestrial and marine environments. Although terrestrial quarantine procedures apply a high level of scrutiny to cargo, there have been no formal guidelines developed to assess the risks associated with marine equipment that may be introduced into Macquarie Island coastal waters. The observations resulted in changes to procedures for the treatment and handling of ANARE watercraft carried on vessels for use as ship-shore transport in the sub-Antarctic islands and Antarctica. There may be merit in DPIWE and/or DTPHA formalizing these measures – potentially in island visit permits – to ensure that

this hazard is not overlooked and that marine bio-security hazards are allocated equivalent scrutiny to terrestrial introduction hazards. Such a requirement should deal with all items of marine equipment and cargo including barges and IRBs, scientific research and sampling equipment, re-supply equipment such as fuel hoses and ropes and also personal items such as SCUBA and snorkeling equipment. As most activities at Macquarie Island access the shore using secondary platforms such as IRBs or LARCs, the quarantine of these objects should also be considered a priority. A significant portion of the response to this hazard[13] should include education of expeditioner and logistic staff associated with national science operations, and also education of private and commercial tourism operators.

Potential Invasive Species

Australia's response to the threat of invasive species has focused on pre-border actions aimed at preventing invasions from occurring. This strategy has relied upon the prevention of introducing or dispersing a number of target pest species around Australia's coastline. The purpose of this approach is to optimize the management of the hazard by allocating resources towards preventing an incursion of species known to possess the ability to establish invasive populations in new regions. It is assumed that by managing these key species, the potential for the translocation of additional non-target species is also reduced. Since 2001, under the auspices of the National System for the Prevention and Management of Marine Pest Incursions, Australia has introduced arrangements, for implementing emergency responses to eradicate newly discovered pests, where feasible, and is developing measures to reduce the incidence of marine pest translocations within Australia.

Owing to the nature of the environmental and physical conditions of Macquarie Island, a species-specific approach to management should be viewed with caution. While most management programs target high traffic port regions that are substantially modified, the management of marine introductions at Macquarie Island must take into account the largely unmodified state of the coastline which includes no artificial structures or permanent docking facilities. Additionally, the coastline includes no large sheltered harbours or anchorages and the exposed rocky shores

[13] A hazard is the feature that creates risk.

are unlikely to offer suitable habitat for the typical pool of target invasive organisms that are suited to establishment in sheltered harbour environments. Although target marine pests are recognized as highly adaptable species capable of establishing in diverse environments, it should be recognised that species not generally considered in species-specific risk assessments may pose a particular risk to Macquarie Island due to its exposed coastline and thermal conditions.

Donor Regions

Although historical traffic has provided links between Macquarie Island and ports as distant as London and Kronstadt in Russia (Cumpston, 1968), most modern vessels visiting Macquarie Island arrive from only a few ports in Australia (Hobart) and New Zealand (Lyttellton, Bluff and Dunedin). Although occasionally traffic originates from other ports (e.g. Fremantle, Melbourne) four ports have been used for the purposes of classifying a pool of target pest species that may invade Macquarie Island. Species known to have been introduced to the primary donor ports of Bluff, Lyttelton, Fremantle and Hobart have been identified through a system of port surveys and are provided in Appendix 2. It should be recognized that some vessels may visit other ports before being committed to operations to Macquarie Island. In the case of most tourism vessels, these may take part in tourism or other operations in the northern hemisphere during the northern summer. Biofouling organisms may be entrained in such localities and the vessels may not be cleaned before embarking on operations to Macquarie Island. It is not known whether a voyage through tropical waters would be sufficient to clear such organisms.

It should also be considered that some vessels do not arrive at Macquarie Island directly from the last port of call but arrive following a voyage to the New Zealand sub-Antarctic islands or Antarctica. Although the short duration of stay in these regions limits the opportunity for species to become entrained on a vessel, Lewis *et al* (2003) demonstrate that Antarctic assemblages are entrained into ballast tanks and transported to temperate regions, and the possibility exists that an Antarctic species of medusan (*Russellia mirablis*) was introduced to the Mediterranean in association with ballast water (Pages *et al.*, 1999). A study of the fouling community of a vessel that visited Heard Island also demonstrated that Southern Ocean organisms are able to recruit to vessel hulls during short visits (Lewis *et al.*, 2004).

The similarity in the environment between Macquarie Island and the nearby New Zealand sub-Antarctic islands suggests that species originating from the latter would have a high likelihood of survival following successful transport to Macquarie Island. Cranfield *et al.*, (1999) identified several introduced marine species present in a number of the New Zealand sub-Antarctic islands:

> Cnidaria:
> *Amphisbitea operculata* (first recorded in Auckland Is, now common in NZ)
>
> Isopoda:
> *Limnora rugosissima* (Snares Island)
>
> Ascidians:
> *Asterocarpa ceres* ("sub-Antarctic islands")
> *Botrylloides leachii* (Auckland Islands)
> *Corella eumyota* ("sub-Antarctic islands" - this species is native to Macquarie Island and distributed throughout the sub-Antarctic region, but is introduced to the European Atlantic)

These species are also likely to be able to survive in Macquarie Island and it should be recognized that these islands may serve as stepping stones facilitating the introduction of invasive species such as the alga *Undaria pinnatifida*[14] to Macquarie Island. Additionally, some species naturally present in the New Zealand sub-Antarctic islands (e.g. the mussel *Mytilus galloprovincialis*) represent risks to Macquarie Island, especially as there are no native mussels with which to compete.

Target Species

As a means of demonstrating the ability of NIS to establish in the coastal environment of Macquarie Island, the thermal tolerances of some highly invasive species have been examined. Table 7.1 shows the thermal tolerance of species for which ballast water management is required (both by AQIS for international shipping and under the terms of the National System)[15] in addition to other highly invasive species. Species have been allocated a high risk ranking if adults are able to survive the entire year in Macquarie Island waters in addition to larval tolerances that enable breeding during the summer period. Species with a low risk rating did not possess tolerances allowing them to complete their life-history cycle at Macquarie Island.

[14] This species has been found on Stewart Island and has resulted in significant concern over introduction to the New Zealand sub-Antarctic Islands.

[15] Originally the Australian Ballast Water Management Advisory Council (ABWMAC) target species list.

Table 7.1: Thermal tolerances of invasive species and hazard of introduction to Macquarie Island. High hazards are allocated to species that are able to complete their life-history cycle at Macquarie Island (Thermal data supplied by CRIMP, 2001).

BALLAST WATER[16] TARGET SPECIES Letters indicate presence at Hobart (H), Lyttelton (L) and Bluff (B)	**LIFE HISTORY STAGE**	**TEMPERATURE TOLERANCE**		**Able to survive at Macquarie Island (Y*= survival for only part of year)**	**Risk (H = High, L= Low)**
		MIN.	**MAX.**		
Asterias amurensis (H)	ADULT	1	30	Y	H
	JUVENILE	1.1	29	Y	
	LARVAE	5	20	Y*	
Carcinus maenas (H)	ADULT	-1	33	Y	L
	GAMETE	10	26	N	
	LARVAE	6	25	Y*	
Crassostrea gigas (H, L, B)	ADULT	-1.8	35	Y	L
	GAMETE	15	30	N	
	JUVENILE	3	35	Y	
	LARVAE	4	35	Y*	
Undaria pinnatifida (H, L, B)	GAMETOPHYTE	-1	30	Y	H
	SPOROPHYTE	0	25	Y	
	ZOOSPORES	5	27	Y*	
Corbula gibba (H)	ADULT	-1	16	Y	H
Sabella sallanzanii (H)	ADULT	2	29	Y	L[+]
Mytilopsis sallei	ADULT	5	40	Y*	L
Alexandrium catenella (H)	ADULT	10	30	N	L
	CYST	4	38	Y*	
Alexandrium minutum	ADULT	12	35.5	N	L
	CYST	4	20	Y*	
Alexandrium tamarense (H)	ADULT	2.5	26	Y	H
	CYST	5	-	Y*	
Gymnodinium catenatum (H)	VEGETATIVE CELL	4	35	Y*	L
	CYST	4	30	Y*	
OTHER SPECIES					
Musculista senhousia	ADULT	0.8	31.1	Y	L
	LARVAE	15	31.1	N	
Mytilus galloprovincialis (H, B, L)	ADULT	0	29	Y	H
Codium fragile ssp. *Tomentosoides* (H)	SPOROPHYTE	-2	27.5	Y	H

[+] *Sabella* prefers sheltered waters.

[16] Formerly Australian Ballast Water Management Advisory Committee (ABWMAC) target list.

Although this is a simplistic approach to highlighting the potential for species to establish in Macquarie Island waters, it demonstrates that seven species typically considered as highly invasive are able to survive in the water temperatures of Macquarie Island. These species are:

- *Asterias amurensis;*
- *Undaria pinnatifida;*
- *Varicorbula gibba;*
- *Sabella spallanzani;*
- *Alexandrium tamarense;*
- *Mytilus galloprovincialis*; and
- *Codium fragile* ssp. *tomentosoides.*

All of the high hazard species are present in the port of Hobart except for the sabellid worm *Sabella spallanzanii,* and two species (*Undaria pinnatifida, Mytilus galloprovincialis*) are present in the ports of Bluff and Lyttelton. Whilst the dinoflagellate *Alexandrium tamarense* is unlikely to be introduced to Macquarie Island due to ballasting practices in the Region, all other species have been shown to be capable of transport in association with hull fouling or in the sea-chests of vessels. Only one species (*Mytilus galloprovincialis*) has been recorded in the fouling communities on Southern Ocean vessels, however no thermal tolerance data is available for the many species that have been recorded in such communities and it is unknown whether these species are capable of establishing in Macquarie Island. The experiment described in Chapter 6 provides additional information on the species that pose a risk to this region.

Risk Assessment

Methodology

Introduction: Risk likelihood and consequence

The Australian Standard for Risk Management (AS/NZ 4360) defines risk as "the chance of something happening that will impact on objectives". Risk is measured in terms of a combination of the probability of an event occurring and the consequence that that event will have. In broad terms, there are three ways a risk assessment can be carried out: quantitative, semi-quantitative or qualitative. Given the paucity of data on factors associated with marine pest invasions in general and on Macquarie Island in particular, and also given the scope of this report, a

qualitative risk assessment is appropriate. A qualitative risk assessment will identify all existing vectors, will describe the risks associated with each vector in each of the stages of marine pest invasion and will therefore be able to propose actions to reduce the risks. Some of the risks will be inherent in a particular vessel type and some will be dependent on activities carried out by the vessel's owners, such as frequency of slipping or dry-docking, and activities carried out by the vessel's crew, such as net cleaning in the case of fishing vessels.

There is reasonable consensus that the process of invasion by marine pests comprises three stages: entrainment, translocation and establishment. There may be some variation of terminology across different research groups, for example, the term entrainment implies an active process by the vessel whereas it is used here as a basket term to include all the entrainment/entrapment/entanglement/colonisation processes whereby a pest organism becomes attached to a vessel's hull or caught up in its gear. Translocation is simply the transport of an organism live to a new location. Establishment is the establishment of a new population at a site distant from the original site. Importantly, successful establishment is as much a function of the receiving environment as the vector responsible for translocation.

In assessing the risks posed by various vectors in translocating marine pests to Macquarie Island, the likelihood of entrainment and translocation has been examined. The likelihood of establishment is impossible to assess as it depends firstly on successful entrainment and successful translocation and secondly a whole set of complex ecological interrelationships. As Bax & Dunstan (2004) explain, "About all that can be said with confidence is that probability of establishment is positively correlated with inoculation frequency and inoculum size." In the case of Macquarie Island probability is likely also to be strongly correlated with temperature tolerance and robustness in the high wave energy environment.

The consequence of a marine pest being entrained by a vector is an increased risk of translocation and, similarly, the consequence of translocation is the possibility of establishment. The consequence of establishment is that an invasive organism becomes established with, potentially, catastrophic consequences but depending on the organism and the receiving environment. Overall risk is therefore more or less confined to the likelihood of entrainment and translocation.

The following table (Table 7.2) summarises the procedure of assessing likelihood and consequence.

Table 7.2: Summary of assessment of likelihood and consequence.

Invasion stage	Likelihood	Consequence
Entrainment	Assessed	Increased likelihood of translocation
Translocation	Assessed	Possibility of establishment
Establishment	Limited assessment based on environmental matching	That a species will become established.

Entrainment risks include:

- ballast water uptake and discharge;
- hull fouling;
- fouling of internal plumbing systems and spaces such as sea chests, which, because of reduced water flow, often harbour larger and more motile organisms;
- entrapment in wet-wells, buckets and bilges;
- entanglement in deck, fishing and anchor gear (eg nets, rope and chain);
- embedding in mud attached to anchors; and
- boring into the hulls of wooden vessels (eg on some cruising yachts).

Translocation risks can be broken down into:

- Volume: the number of vessels plying a route;
- Range: the average distance over which vessels in the sector travel;
- Frequency: how often vessels ply a route; and
- Promiscuity: the number of discrete locations vessels visit.

In terms of considering the risks of invasion by marine pests in general, and at Macquarie Island in particular, it is necessary to consider the risks, i.e. probability and consequence associated with each of these stages (entrainment, translocation and establishment).

Risk assessment

The first stage of the risk assessment is to identify all existing and potential vectors. Table 7.3 is a risk matrix, specifying the vectors and the principal factors in entrainment and translocation. Vectors are grouped by similar vessel and operational characteristics.

Table 7.3: Vector risk matrix.

Vector group	Numbers (2000 – 2004)	Home port(s)	NIS in home port?	Risk types Entrainment	Risk types Translocation
Research vessels & resupply vessels	14	Hobart and others	Yes (in Hobart)	Hull fouling Ballast water Research gear	Range Frequency
ANARE watercraft	Not known in detail	Hobart	Yes	Hull fouling	Range Frequency
Fishing vessels	4[1]	Fremantle Albany	Yes	Hull fouling Fishing gear	Range
Tourist vessels	29	Not known[2]	May be a donor region for a number of invasive organisms[3]	Hull fouling Ballast water	Range Frequency Promiscuity
Cruising yachts	No records	Varies	Not known	Hull fouling	Range
Marine debris	>1,000 items per year[4]	N/A	N/A	Fouling	Range Frequency

Notes:
1. Data provided by AFMA.
2. These vessels are chartered from Russian operators, such as Far Eastern Shipping Company (FESCO), which operates out of Vladivostok.
3. *Asterias amurensis* (Northern Pacific seastar), for example, is native to the bioregion where Vladivostok is located.
4. c. 1200 plastic items of varying sizes July 2000 – July 2001.

Entrainment and translocation risks by Macquarie Island vectors

The following section sets out a risk assessment of each vector group. There are six groups of potential vectors, as identified above. The risk assessment identifies examples of vessels in each group and provides a brief description of those vessels. Entrainment and translocation risks are also identified followed by a number of management measures to mitigate the risks.

RESEARCH VESSELS AND RE-SUPPLY VESSELS

Examples:

RSV *Aurora Australis*, RV *Southern Surveyor*, MV *Polar Bird*

Description

These vessels are characterized by being primarily Antarctic research and re-supply vessels and are predominantly, though not exclusively, chartered by the Antarctic Division for ANARE operations. *Southern Surveyor*, for example, is the National Facility Research vessel operated by

CSIRO. This vessel is resident in Hobart and has visited Macquarie Island on at least one occasion.

RSV *Aurora Australis* ("*Aurora*") is the Antarctic Division's main research and re-supply vessel which has been used every season since 1990. *Aurora* typically spends up to eight months of the year at sea on research and re-supply voyages and four months tied up in the docks in Hobart, during which time it accumulates significant build-up of fouling as the hull is painted with an abrasion resistant epoxy coating which does not contain a biocide. This fouling is scraped off areas of the hull exposed to ice during the first encounter with pack ice[17]. While this may be a pragmatic solution to hull fouling, it cannot be recommended as best practice. There are risks in translocating marine organisms to the Antarctic continent and the sub-Antarctic islands and a fouled hull will have a detrimental effect on fuel consumption. It must however be recognized that annual dry docking and application of antifoulant coating will be prohibitively expensive, additionally the pack ice will erode the antifoulant coating thereby releasing toxic materials into the Antarctic environment.

Polar Bird (previously named *Ice Bird*) has not been chartered by the Antarctic Division since 2000 but prior to that was used extensively over a long period. It is used here as an example of a vessel which is chartered for the summer field season but, unlike *Aurora*, is not resident in Hobart and comes in from a previous charter, potentially from anywhere in the world. Such a vessel would typically spend a few days in Hobart at the beginning of the charter and then a few days between each voyage.

Entrainment risks

- Hull fouling from long lay ups in port over winter
- Hull and antifoulant condition and currency
- Use and exchange of ballast water
- Use of research gear e.g. CTD, fishing net, on board water sampling apparatus
- Use of auxiliary craft e.g. Zodiacs, life boats (used in drills in Hobart docks)
- Use of anchors

[17] It is also likely that Antarctic sea water temperatures would cause mortality to all but the hardiest organisms and those protected by sea chests.

Translocation risks

- Short voyage time from Hobart direct to Macquarie Island
- Hulls not fully protected with antifoulant

Management measures

The hulls of these vessels represent a major translocation risk, especially after the long lay up in Hobart docks in winter. If the current regime of antifoulant application is to be continued, the following management measures are recommended:

1. Vessel hull cleanliness and antifoulant currency are critical to reduce entrainment and translocation risks. Recommended biofouling control measures include:
   - Regular dry-docking for hull and sea chest cleaning, as close as possible to the beginning of Southern Ocean operations;
   - If no other treatments are possible, *Aurora Australis* should not make its first voyage after winter direct to Macquarie Island. If this is unavoidable, the vessel should not approach closer than where the water depth is less than 200m.
   - Application and maintenance of effective antifoulants, but as environmentally benign as possible;
   - Where dry dock or operational schedules do not allow for annual cleaning and antifoulant application, vessels with a long residency in Hobart should consider in-water[18] hull cleaning, for example by diver or other means;
   - Vessel hull cleanliness and antifoulant currency should be made part of the charter conditions for vessels coming on charter. Vessels should arrive in Hobart with their antifoulant systems up-to-date and hulls clean.
2. Ballast water must not be released within 200 nautical miles of the island (IMO Guidelines);
3. All scientific equipment (e.g. CTD) and operational gear (e.g. Zodiacs and life boats) tested in coastal waters in Tasmania should be thoroughly cleaned with fresh water and inspected for organisms before stowage;

[18] In-water hull cleaning is generally not recommended but in this case where the biofouling has originated within Hobart docks, it seems reasonable to clean the hull in that environment. As far as possible, hull scrapings should be retained and disposed of in landfill.

4. The water sampling system should not be made operational until the vessel has reached a water depth of greater than 200 metres to avoid ingestion of larvae, etc;
5. Ships anchors, if used in Tasmanian coastal waters, should be cleaned of all sediment with a high pressure hose before stowage.

NB: A specific asessessment and set of recommendations for the primary resupply vessel *Aurora Australis,* is provided in Appendix 3.

ANARE WATERCRAFT

Example:

Barges
LARCs

Description

These are small craft (about 10m length with shallow draft) which are used as lighters to ferry stores and other material from ship to shore and vice-versa. They are self-propelled using an in-board engine. LARCs also have wheels and are able to drive up onto beaches.

Entrainment risks

- Hull fouling from long lay ups in port over winter
- Entanglement on anchor/mooring warps

Translocation risks

- Short voyage time from Hobart direct to Macquarie Island – organisms entrained on hull can survive emersed.

Management measures

1. Barges and other watercraft left in the water in Hobart for extended periods should be brought out onto dry land, thoroughly hosed down with fresh water and left to dry out for at least three days. The craft should be thoroughly inspected before loading onto the ship.

FISHING VESSELS

Examples:

FV *Southern Champion*
FV *Austral Leader* (retired)

Description

Vessels licenced to fish in the Macquarie Island Fishery. FV *Southern Champion* is a large vessel (87m length) whose home port is Fremantle, WA but is based in Albany. *Southern Champion* is slipped, cleaned and antifouled annually.

Entrainment risks

- Hull fouling from port residency and aged or damaged antifoulant system
- Use and exchange of ballast water
- Use of fishing gear especially net.

Translocation risks

- Depends on where vessel sails from. The distance from Albany is approximately 3800 km; compare with the distance from Hobart which is 1550 km. The risk factors generally diminish with increasing distance.

Management measures

1. The vessel's owner should be encouraged to maintain the antifoulant system and hull cleanliness. This should also include the internal water system, recessed areas and wet areas;
2. Fishing gear should be thoroughly cleaned, dried and inspected before deployment in Macquarie Island waters; any organic material discovered on the gear should be retained on board and disposed of in landfill on the vessel's return to the mainland;

TOURISM VESSELS

Examples:

Akademic Shokalskyi , *Kapitan Khlebnikov* and *Spirit of Enderby*

Description

These vessels are chartered from owners in Russia. All are ice class vessels; *Akademic Shokalskyi* and *Spirit of Enderby* are oceanographic research vessels, while *Kapitan Khlebnikov* is an ice-breaker.

Entrainment risks

- Hull fouling from port residency and aged or damaged antifoulant system
- Use and exchange of ballast water
- Use of auxiliary craft e.g. Zodiacs, life boats (used in drills in Hobart docks)
- Use of anchors

Translocation risks

- Short voyage time from Hobart, Bluff, Dunedin and Lyttelton direct to Macquarie Island

Management measures

1. The vessel's owner should be encouraged to maintain the antifoulant system and hull cleanliness. This should also include the internal water system, sheltered recesses and interstices, and wet areas;
2. Ballast water must not be released within 200 nautical miles of the island (IMO Guidelines);
3. All operational gear (e.g. Zodiacs and life boats) tested in coastal waters in Tasmania and New Zealand should be thoroughly cleaned with fresh water and inspected for organisms before stowage;
4. Ships anchors, if used in Tasmanian or New Zealand coastal waters, should be cleaned of all sediment with a high pressure hose before stowage.

CRUISING YACHTS

Examples:

Spirit of Sydney, while not having visited Macquarie Island, has visited Cape Denison in Antarctica on numerous occasions so is clearly capable of making this voyage. At least one private yacht is known to have visited Macquarie Island in recent times.

Description

Cruising yachts tend to be relatively large vessels of this class. *Spirit of Sydney* is 18.2 m in length.

Entrainment risks

- Hull fouling from port residency and aged or damaged antifoulant system
- Relatively slow speed may allow organisms to settle on the hull
- Use of auxiliary craft e.g. tenders
- Use of anchors

Translocation risks

- Short distance from likely departure ports such as Hobart and Bluff

Management measures

1. Hull cleanliness is critical to minimizing marine pest introduction risks. The owners of vessels planning to visit Macquarie Island should be required to provide evidence of antifoulant currency before a permit to visit the island is granted. Inspecting the hull before departure may be beneficial but may not be possible or enforceable if the vessel approaches the island from New Zealand. Education and awareness-raising may be all that is required to achieve a high rate of compliance.
2. Tenders should be thoroughly cleaned with fresh water and inspected for organisms before stowage.
3. Anchors should be cleaned of all sediment before stowage.

ANTHROPOGENIC DEBRIS

Examples:

Lost fishing gear

Material jettisoned from ships

Description

Anthropogenic debris takes many shapes and forms and can be categorized as follows:

- Fishing debris (e.g. nets, buoys, rope)
- Dunnage (wooden ship-board storage and packaging)
- Rubbish (e.g. plastic drink bottles)

Entrainment risks

Low entrainment risks. IMO regulations (MARPOL) prohibit the dumping into the sea of all types of plastic (IMO 2006). Debris jettisoned at or lost at sea is not likely to entrain invasive organisms. Organisms that colonise debris floating in mid-ocean are likely to be cosmopolitan species such as gooseneck barnacles.

Translocation risks

Low translocation risks. Floating debris can only move with the winds and currents. In the Southern Ocean these are predominantly from west to east with very limited north - south transport. The paucity of timber washed up on the shoreline of Macquarie Island provides concrete evidence that this is not likely to be an important vector of marine pests from temperate regions.

Management measures

1. Marine debris presents far higher risks to the environment from entanglement and ingestion by wildlife than as a potential vector of marine pests. Any action taken to reduce the quantity of anthropogenic debris in the world's oceans will be beneficial for all these reasons.
2. It is recommended, however, that TASPAWS Rangers regularly monitor the island's shoreline, looking out, in particular, for attached or encrusting organisms, on marine debris, especially mussels.

Discussion

The intent of this report is to assess the risk of marine pest introductions to the Macquarie Island Marine Park. It has been unavoidable, however, not to focus on shipping traffic to the island itself and marine debris washed up on its shores. The ANARE research station at Macquarie Island is the focus of shipping activity in the Region and the shallow coastal zone surrounding the island provides the most suitable habitat for potentially invasive species. Virtually all invasive organisms have become established in shallow water; usually less than 100 metres deep, though some are able to survive in water depths up to 200 m. *Asterias amurensis*, for example, has been recorded at a depth of 200 m in its native Japan, but not in Australian waters (NIMPIS 2002b). The concentration of vessel activity in the Buckles Bay and Hasselborough Bay region, and the residence of vessels for up to five days in the vicinity of the island results in the highest risk of invasion in the shallow waters adjacent to the island. Invasive species established within the coastal zone of Macquarie Island may subsequently extend their range into the marine park, and particularly to portions of the Marine Park with a depth less than 200m. Thus the major risk to the Macquarie Island Marine Park is from the secondary dispersal of invasive organisms previously established on the island rather than from an introduction within the limits of the Marine Park itself.

Vessels residing in port regions for long periods, especially those vessels without antifoulant or with incomplete antifoulant protection represent a major risk of translocating invasive marine species. All ports contributing traffic to the Region are known to host populations of several highly invasive species (see Appendix 2) and given the short transit distances to the island it is suggested that the risk of entrainment and translocation is high. As noted in previously, the final link in the chain of events leading to an introduction is the establishment of an organism in a new location. Assessing the risks of establishment involves more than matching environmental tolerances and relates to inoculum frequency and size, trophic niches, ecological health, environmental disturbance and other factors. At Macquarie Island a significant additional factor is the high wave energy that pounds the coastline for much of the year and the absence of sheltered harbours. Thus, while the entrainment and translocation risks are high, the risks of establishment in the Region are unknown, but potentially low. A better understanding of the

factors and processes involved in the establishment of an invasive marine species in a new location will be required before a fuller assessment is possible. A rapid response to known introductions is essential if attempts at eradication are to be successful (McEnnulty *et al.*, 2001) and an emergency response plan specific to the conditions of Macquarie Island should be drawn up now. In addition, it should be noted that the chances of eradicating a pest organism, once it has become established, is likely to be low.

At the time of writing, a number of other initiatives which are relevant to efforts to prevent marine pest introductions at Macquarie Island are being developed and implemented under the auspices of the National System for the Prevention and Management of Marine Pest Incursions (DAFF 2006), "the National System". These include the development of guidelines for the management of biofouling on ships hulls, guidelines for the commercial fishing industry and for small international vessels. The recommendations made in this report are consistent with the guidelines being developed under the terms of the National System.

Recommendations

Given the uncertainty of risks of establishment, it is thought that the best way to protect the Marine Park is to monitor the shoreline and near-shore waters where shipping operations take place. It is therefore recommended that a baseline survey be conducted in Garden Cove and Landing Beach and the rocks in the near vicinity and in one or two sheltered locations on the Hasselborough Bay side of the isthmus. Information packs, posters and sessions should be developed for Tasmanian Parks and Wildlife Service Rangers to be part of their training package prior to their deployment to the island. They should be encouraged to patrol the shoreline in the vicinity of the station and along the west coast to look for unusual organisms. If an unfamiliar organism is found, it could be photographed with a digital camera and the image sent to the Tasmanian Museum for identification. A plan of action for dealing with a possible introduction should be drawn up through the Consultative Committee on Introduced Marine Pest Emergencies (CCIMPE).

Summary of recommendations from risk assessments:

- Ballast water must not be released within 200 nautical miles of the island (IMO Guidelines);
- Vessel hull cleanliness and antifoulant currency are critical to reduce entrainment and translocation risks. If these are not possible, voyages to Macquarie Island by *Aurora Australis* and other vessels with a long residency in Hobart should be via the Antarctic continent.
- All scientific equipment (e.g. CTD) and operational gear (e.g. Zodiacs, life boats and tenders) should be thoroughly cleaned with fresh water and inspected for organisms before stowage. Research vessels' water sampling systems should not be made operational until the vessel has reached a water depth of greater than 200 metres out of port;
- Barges and other watercraft left in the water for extended periods should be brought out onto dry land, thoroughly hosed down with fresh water and left to dry out for at least three days. The craft should be thoroughly inspected before loading onto the ship.
- Fishing gear should be thoroughly cleaned, dried and inspected before deployment in Macquarie Island waters; any organic material discovered on the gear should be retained on board and disposed of in landfill on the vessel's return to the mainland;
- All anchors should be cleaned of sediment with a high pressure hose before stowage.
- TASPAWS Rangers should regularly monitor the island's shoreline, looking out, in particular, for attached or encrusting organisms, on marine debris, especially mussels.

Section V

Discussion and Conclusions

Chapter 8: Discussions and Conclusions

The process of marine introductions has been well studied in most regions, however this work, in conjunction with an earlier publication (Lewis *et al.*, 2003), represents the first detailed study of the threat of marine introductions in high-latitude coastlines of the Southern Hemisphere. To provide a comprehensive assessment of this issue, a holistic approach has been employed whereby a variety of tools have been utilised to gather information on the entire transport pathway. Thus the thesis is divided into a number of section that deal with the entire process of introduction from the initial association of an organism with a potential transport vector, through to an assessment of the ability of marine communities from a temperate port to survive in the thermal conditions of the Southern Ocean.

Transport Vectors

Two major modes of transport have been described in the literature: floating plastics (Barnes, 2004) and vessel based transport mechanisms. Plastic debris do provide an opportunity for the dispersal of invasive organisms, but dispersal routes are passive, dependent on ocean currents, and kelp rafts already provide transport opportunities over the same spatial and temporal scale. Thus the focus of concern should be directed towards vessel-based vectors of transport that are capable of rapidly delivering NIS across large geographical scales.

Comprehensive surveys of a variety of vessel types demonstrated that modern vessels typically visiting high-latitude coastlines in association with tourism, science and fishery operations host diverse assemblages of organisms. While ballast water is an important transport pathway in many regions, the ballasting requirements of Southern Ocean operations do not require the discharge of ballast-water in high-latitude waters. Thus hull fouling was demonstrated to be the highest risk pathway associated with shipping operations capable of delivering communities of up to 56 species to high latitude coastlines. As these communities recruit to the hull from highly invaded port environments they incorporate a large proportion of NIS and in some instances, 50% of the species from these communities were considered non-indigenous in some portion of their range.

Marine equipment loaded aboard vessels is also shown to be a viable delivery mechanism for NIS, capable of delivering a diverse and healthy fouling community directly to the sub-Antarctic islands. Whereas the mitigation of fouling is a complex issue requiring further research, items of marine cargo are able to be screened in a similar manner to cargo destined for the terrestrial environment. The findings of this study have resulted in a change in the quarantine procedures applied to marine cargo shipped be the Australian Antarctic Division. Operators in the Southern Ocean need to develop quarantine procedures that specifically target marine cargo to ensure that such items do not avoid sufficient scrutiny.

The assessment of transport pathways clearly demonstrates that a variety of marine species, many of them invasive, are frequently entrained upon the platforms used to access the Southern Ocean. Furthermore, it is clear that in the absence of sea-ice, no barriers exist that are sufficient to remove entrained organisms from the hull of vessels. Communities are capable of surviving return voyages to the most remote of the sub-Antarctic islands so clearly viable individuals are available for release upon arrival at these destinations.

The management of hull fouling should be considered as the primary tool to limit the transfer of NIS into the Southern Ocean. Simple approached to minimizing fouling include the avoidance of prolonged port-layovers during winter, the routing of voyages through sea-ice which may physically remove attached organisms from the hull, and the reliance upon effective antifouling paints. Recent concerns over the impact to Antarctic environments from toxic paints should be viewed in balance with the potential impacts from introduced marine pests which may be advantaged by any broad ban upon antifouling paints in the region.

Genetic introductions

NIS are not the only threat to biodiversity created by anthropogenic transport pathways. A more subtle problem is the introduction of foreign genetic material to isolated populations. The issue of genetic introductions is gaining prominence in the scientific literature and remote populations such as those in Antarctica and the sub-Antarctic islands are particularly vulnerable to hybridization with closely related species or sub-species that may be liberated by human activities. An assessment of a widely distributed species, *Mytilus gallioprovincialis* (blue mussels) demonstrates that remote populations in the New Zealand sub-Antarctic islands should be

considered as a sub-species. These populations possess a greater level of genetic diversity within the target mitochondrial regions (COI) that the entire Mytilus species complex. Isolated populations with unique genotypes represent valuable examples of genetic information in species such as *M galloprovincialis* which possess a genetic population structure that has been clearly homogenized as a result of human transport opportunities. The ability of invasive species such as the Mytilus complex to gain rapid dispersal in association with anthropogenic transport vectors threatens the genetic diversity of such species. This loss of genetic diversity is an additional component of biodiversity loss associated with the spread of NIS.

Thermal tolerance of invaders

Having described the operation of various transport mechanisms for NIS, it is important to assess the possible array of species that may achieve successful transport. By identifying high risk species, surveillance and monitoring activities can focus upon species of concern, allowing resources to be allocated more efficiently. Due to the unique nature of the environment of the Southern Ocean it is unlikely that the list species typically classified as high risk in temperate ports will adequately address those species of concern to high-latitude coastlines. Although some wide spread invasive species will inevitably pose a hazard, it is also likely that the extreme temperatures and high energy coastlines of this region will provide an opportunity for the establishment of some species not generally considered as invasive in the estuarine ports that typify the habitats of most invasive species.

To provide a broad assessment of which temperate species pose a hazard to Antarctica and the sub-Antarctic islands, fouling communities were collected on settlement plates and exposed to thermal conditions replicating these environments. This approach provides a rapid and effective method to quickly assess the pool of potential invaders to this region. It was demonstrated that a wide variety of species could survive the thermal conditions of the sub-Antarctic islands and that at least eight species found within the temperate port of Hobart could survive in the waters of Antarctica. In the case of three species (*Halicarcinus innominatus, Petrolisthes elongatus* and *Mytilus galloprovincialis*) it was also demonstrated that they were capable of spawning and completing their entire life-history cycle at these temperature.

Risk assessment

The information gathered during the course of this research is intended for utilisation in the sound management of marine introductions in high-latitude ecosystems. Chapter 7 of the thesis incorporates several aspects of this research in a risk assessment examining the risks of introduction of non-indigenous marine species to the Macquarie Island Marine Park. This assessment provides specific management advice for various vectors operating on this island. The recommendations include conducting a baseline survey to determine that no invasive species has already taken hold and a program of education and awareness-raising is proposed for Tasmanian Parks and Wildlife Rangers to look out for unusual marine organisms as part of their duties on the island.

* * * *

It is clear that NIS are being delivered to high-latitude coastlines, and that many species are capable of surviving in these environments at least for short periods. However, apart from the recent report of the north Atlantic spider crab (Tavares & De Melo, 2004), some cosmopolitan algae (Clayton *et al.*, 1997) from the Antarctic Peninsula and a few reports of introduced species from the New Zealand sub-Antarctic islands (Cranfield *et al.*, 1998) there are virtually no records of non-indigenous marine species from these regions. This scarcity of reported introductions is unlikely to reflect a real paucity of introductions and probably stems from the lack of surveys conducted in the region and also from the tendency to assume species found in such remote waters must be native. For example, several species of ascidians (*Bathystyeloides enderbyanus, Cnemidocarpa bythia, Corella eumyota, Proagnesia depressa* – Primo & Vazquez, 2004) and bryozoa (*Aetia anguina &Scruparia ambigua* – Hayward, 1995) reported from Antarctica are also found in the waters of the Northern Hemisphere and it cannot be assumed that they have not been introduced to the Southern Ocean (Hewitt & Lewis, 2006).

An additional component of this project was to undertake base line surveys of the New Zealand Auckland Islands and at Macquarie Island (see Appendix 4) and to determine the extent of introductions at these islands. Due to the long process of taxonomic verification (taxonomic experts consulted are listed in Appendix 5) and the limited taxonomic resources available for the sub-Antarctic islands (and to some extent throughout the world), the results of these surveys are

presently incomplete; however a preliminary species list is provided in Appendix 5 (Auckland Islands) and Appendix 6 (Macquarie Island).

While preliminary outcomes of the survey have verified the presence of introduced ascidian *Botrylloides leachii* at the Auckland Islands, and several cryptogenic species from both regions, the outcome of these surveys should not be considered as a comprehensive base-line assessment for introduced species. Surveys were opportunistic and could not be conducted with the rigor required to effectively sample the entire community. For example the inability to utilise SCUBA at Macquarie Island limited the survey to inter-tidal and shallow sub-tidal environments. Although basic in nature, the surveys do provide an accurate assessment of the common species observed in each environment and in the case of the Auckland Island survey several species not previously recorded from the island were observed. It is intended that the methods and results from these surveys be taken into account during the design and implementation of a more rigorous survey program allocated with sufficient resources to establish a robust base-line record of the marine communities at each sub-Antarctic island.

A focus upon the mitigation of transport in association with specific vectors such as hull fouling should be the primary objective for the management of invasive species in high-latitude coastlines. Although such a focus would clearly limit the transmission of NIS, it is almost inevitable that some species will slip through the barriers. As a result, the management of vectors should be undertaken in conjunction with a rigorous system of surveillance and monitoring. A system of base-line surveys based upon the methodology described in Appendix 4 would be the fist step in appropriate surveillance for these regions and would collate sufficient taxonomic information to effectively identify introduced and cryptogenic species. Once such a base-line is established, routine monitoring can be conducted at a relatively low cost by staff on the ground (see chapter 7) and also through the deployment of rapid monitoring tools such as settlement plates retrieved periodically (de Rivera *et al.*, 2005). The latter has the advantage of providing a low-tech approach that can be rapidly deployed and retrieved during a short visit for subsequent analysis in laboratories in Australia or New Zealand.

* * * *

The past three years have witnessed a growing prominence of the problem of NIS and particularly marine introductions in high latitude coastlines. In addition to papers published from the current body of work, publications examining the introduction of a NIS of spider crab to the Antarctic Peninsula (Tavers & De Melo, 2006), and the discussion of introductions in association with floating plastic debris (Barnes 2002, Barnes & Fraser 2003) have contributed to a growing awareness of this problem and a commitment to manage this threat proactively.

Climate change and the accelerating rate of visitation to the coastlines of the Southern Ocean mean that the threat of introductions in this region in accelerating rapidly (Chown *et al.*, 2005). Although many gaps remain in our present understanding of the process of marine introductions in Antarctica and the sub-Antarctic islands, it is essential that measure be taken on a precautionary basis to conserve the unique biodiversity of these waters. The outcome of the current thesis contributes significantly to the large gaps in information that are preventing the instigation of immediate management measures for this region.

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Appendix 1: Species recorded on settlement plates in thermal trial

Table A1: Species recorded from plates maintained at 0°C. Plates from A-D were collected at T1 (27 May, 2005); Plates from E-H were collected from T2 (25 July, 2005).

	0A	0B	0C	0D	0E	0F	0G	0H
Ascidian sp1	0	0	0	0	1	0	0	0
*Botrylloides leachii**	0	0	0	0	0	0	0	0
Ciona intestinalis	1	1	0	0	1	0	1	1
Cnemidocarpa radicosa	0	0	0	0	0	0	0	0
Herdmania momus	0	1	0	1	0	1	0	0
Pyura stolonifera	0	0	0	0	0	0	0	0
Bryozoa sp1	0	0	0	0	0	0	0	0
Bryozoa sp2	0	0	0	0	0	0	0	0
Bugula flabellata	0	0	0	0	0	0	0	0
*Watersiporia subtorquata**	0	0	0	0	0	0	0	0
Balanus variegates	1	0	0	0	0	0	1	0
*Corophium acherusicum**	0	0	0	0	0	0	0	0
*Elminius modestus**	0	0	0	0	0	0	0	0
Ericthonius sp.	0	0	0	0	0	0	0	0
*Halicarcinus inomminatus**	0	0	0	0	0	0	0	0
Halicarcinus ovatus	0	0	0	0	0	0	0	0
Munida sp.	0	0	0	0	0	0	0	0
Notomithrax minor	0	0	0	0	0	0	0	0
Palaemon dolospina	0	0	0	0	0	0	0	0
Palaemon intermedius	0	0	0	0	0	0	0	0
Parawaldeckia sp.	0	0	0	0	0	0	0	0
*Petrolisthes elongatus**	0	0	0	0	0	0	0	0
Pinnotheres hickmani	0	0	0	0	0	0	0	0
Sphaeromatidae sp1	0	0	0	0	0	0	1	0
Pateriella regularis	0	0	0	0	0	0	0	0
Hirudinea sp.	0	0	0	0	0	0	0	0
Clytia sp.	0	0	0	0	0	0	0	0
Hydroid sp1	0	0	0	0	0	0	0	0
Hydroid sp2	0	0	0	0	0	0	0	0
Aplysia sydneyensis	0	0	0	0	0	0	0	0
*Crassostrea gigas**	1	0	1	0	1	1	0	1
Hiatella australis	0	0	0	0	0	0	0	0
Irus (Irus) cumingii	0	0	0	0	0	0	0	0
Muscula impacta	0	0	0	0	0	0	0	0
*Mytilus galloprovincialius**	1	1	1	1	1	1	1	1
Nudibranch sp1	0	0	0	0	0	0	0	0
Notoplana australis	0	0	0	0	0	0	0	0
Boccardia polybranchia	0	0	0	0	0	0	0	0
Cirriformia sp.	0	0	0	0	0	0	0	0
Dorvelleid sp.	0	0	0	0	0	0	0	0
Harmothoe waahli	0	0	0	0	1	1	1	1
Neanthes cricognatha	0	0	0	0	0	0	0	0
Ophiodromus sp.	0	0	0	0	0	0	0	0
Polynoidae sp1	0	0	0	0	0	1	0	0
Pomatoceros taeniata	0	0	0	0	0	0	0	0
Spirorbid sp.	0	0	0	0	0	0	0	0
Porifera sp1	0	0	0	0	0	0	0	0
Porifera sp2	0	0	0	0	0	0	0	0
Porifera sp3	0	0	0	0	0	0	0	0
Porifera sp4	0	0	0	0	0	0	0	0
Total	4	3	2	2	5	5	5	4

Appendix 1: Species recorded on settlement plates in thermal trial

Table A2: Species recorded from plates maintained at 5°C. Plates from A-D were collected at T1 (27 May, 2005); Plates from E-H were collected from T2 (25 July, 2005).

	5A	5B	5C	5D	5E	5F	5G	5H
Ascidian sp1	1	1	1	1	1	1	0	1
*Botrylloides leachii**	1	1	1	1	1	0	0	1
Ciona intestinalis	1	1	1	1	1	1	1	1
Cnemidocarpa radicosa	0	0	0	0	0	0	0	0
Herdmania momus	1	0	1	1	1	0	0	0
Pyura stolonifera	1	1	1	1	1	1	1	1
Bryozoa sp1	0	0	0	0	0	0	0	0
Bryozoa sp2	0	0	0	0	0	0	0	0
Bugula flabellata	1	1	0	1	0	1	1	0
*Watersiporia subtorquata**	0	1	0	1	0	0	0	0
Balanus variegates	1	1	1	1	1	1	0	1
*Corophium acherusicum**	0	0	0	0	0	0	0	0
*Elminius modestus**	0	0	0	0	0	0	0	0
Ericthonius sp.	0	1	0	1	1	0	1	0
*Halicarcinus inomminatus**	1	1	1	1	1	1	1	1
Halicarcinus ovatus	0	0	0	0	0	0	0	0
Munida sp.	0	0	0	0	0	0	0	0
Notomithrax minor	0	0	0	0	0	0	0	0
Palaemon dolospina	1	0	0	0	0	0	1	0
Palaemon intermedius	0	1	1	0	0	1	0	0
Parawaldeckia sp.	1	1	1	1	1	1	1	1
*Petrolisthes elongatus**	1	1	1	1	1	1	1	1
Pinnotheres hickmani	0	1	0	0	1	0	1	1
Sphaeromatidae sp1	0	0	0	0	0	0	1	0
Pateriella regularis	0	0	0	0	1	0	1	0
Hirudinea sp.	0	0	0	0	0	0	0	0
Clytia sp.	0	1	0	1	0	0	0	0
Hydroid sp1	0	0	0	0	0	0	0	0
Hydroid sp2	0	0	0	0	0	0	0	0
Aplysia sydneyensis	0	0	0	0	1	0	0	0
*Crassostrea gigas**	1	1	1	1	1	1	1	1
Hiatella australis	1	1	1	1	0	1	1	1
Irus (Irus) cumingii	0	0	0	0	0	0	0	0
Muscula impacta	0	0	0	0	0	0	0	0
*Mytilus galloprovincialius**	1	1	1	1	1	1	1	1
Nudibranch sp1	0	0	0	0	0	0	0	0
Notoplana australis	0	0	0	0	0	0	0	1
Boccardia polybranchia	1	0	1	0	1	0	1	0
Cirriformia sp.	1	1	0	1	0	1	1	0
Dorvelleid sp.	0	0	0	0	0	0	0	0
Harmothoe waahli	1	1	1	1	1	1	1	1
Neanthes cricognatha	0	1	0	1	0	0	1	0
Ophiodromus sp.	0	0	0	1	0	1	0	0
Polynoidae sp1	1	1	0	0	1	0	1	0
Pomatoceros taeniata	1	1	0	1	1	1	0	0
Spirorbid sp.	0	0	0	0	0	0	0	0
Porifera sp1	0	0	0	0	0	0	0	0
Porifera sp2	0	0	0	0	0	0	0	0
Porifera sp3	0	0	0	0	0	0	0	0
Porifera sp4	0	0	0	0	0	0	0	0
Total	19	22	15	21	19	16	19	14

Appendix 1: Species recorded on settlement plates in thermal trial

Table A3: Species recorded from plates maintained at 13ºC. Plates from A-D were collected at T1 (27 May, 2005); Plates from E-H were collected from T2 (25 July, 2005).

	13A	13B	13C	13D	13E	13F	13G	13H
Ascidian sp1	1	1	1	1	1	1	1	1
*Botrylloides leachii**	1	1	1	1	1	1	1	1
Ciona intestinalis	1	1	0	1	1	1	1	0
Cnemidocarpa radicosa	0	1	1	0	0	0	0	1
Herdmania momus	1	1	1	1	1	1	1	0
Pyura stolonifera	1	1	1	1	1	1	1	1
Bryozoa sp1	0	0	0	0	0	0	0	0
Bryozoa sp2	0	1	0	0	0	0	0	0
Bugula flabellata	1	1	1	1	0	1	1	1
*Watersiporia subtorquata**	1	1	0	1	1	1	1	0
Balanus variegates	1	1	0	1	1	0	1	1
*Corophium acherusicum**	0	0	0	0	0	0	0	0
*Elminius modestus**	0	0	0	0	1	0	0	0
Ericthonius sp.	0	1	0	0	1	1	0	1
*Halicarcinus inomminatus**	1	1	1	1	1	1	1	1
Halicarcinus ovatus	0	1	0	1	1	0	0	1
Munida sp.	0	0	1	0	1	0	0	0
Notomithrax minor	1	0	0	0	0	0	0	1
Palaemon dolospina	0	0	0	0	0	0	1	0
Palaemon intermedius	0	1	0	1	0	1	0	0
Parawaldeckia sp.	1	1	1	1	1	1	0	1
*Petrolisthes elongatus**	1	1	1	1	1	1	1	1
Pinnotheres hickmani	0	1	0	1	0	1	1	0
Sphaeromatidae sp1	0	0	0	0	0	0	1	0
Pateriella regularis	1	0	1	0	1	0	1	1
Hirudinea sp.	0	0	0	0	0	0	0	1
Clytia sp.	0	0	0	0	0	0	0	0
Hydroid sp1	1	0	0	0	1	0	1	0
Hydroid sp2	1	0	0	0	1	1	1	1
Aplysia sydneyensis	0	1	0	0	0	0	0	0
*Crassostrea gigas**	1	1	1	1	1	1	1	1
Hiatella australis	1	1	0	1	1	1	1	1
Irus (Irus) cumingii	0	1	0	0	0	1	0	0
Muscula impacta	1	1	1	1	1	1	1	1
*Mytilus galloprovincialius**	1	1	1	1	1	1	1	1
Nudibranch sp1	1	1	1	0	1	0	0	0
Notoplana australis	1	1	0	1	0	0	1	1
Boccardia polybranchia	0	1	1	1	1	1	0	0
Cirriformia sp.	1	1	1	1	1	1	1	1
Dorvelleid sp.	0	0	0	0	0	0	0	0
Harmothoe waahli	1	1	1	1	1	1	1	1
Neanthes cricognatha	1	0	1	1	1	1	1	1
Ophiodromus sp.	0	0	0	0	0	0	1	0
Polynoidae sp1	1	1	1	1	1	1	1	0
Pomatoceros taeniata	1	0	1	1	0	1	1	1
Spirorbid sp.	0	0	0	1	0	0	0	0
Porifera sp1	0	0	0	0	1	0	1	0
Porifera sp2	0	0	0	0	1	0	0	0
Porifera sp3	0	0	0	0	0	0	0	0
Porifera sp4	0	0	0	0	0	0	0	0
Total	26	29	21	26	29	25	28	24

Appendix 1: Species recorded on settlement plates in thermal trial

Table A4: Species recorded from plates maintained at 25ºC. Plates from A-D were collected at T1 (27 May, 2005); Plates from E-H were collected from T2 (25 July, 2005).

	25A	25B	25C	25D	25E	25F	25G	25H
Ascidian sp1	0	0	1	0	1	0	1	1
*Botrylloides leachii**	0	1	0	0	0	0	0	0
Ciona intestinalis	1	0	1	1	1	1	1	1
Cnemidocarpa radicosa	0	0	0	0	0	0	0	0
Herdmania momus	0	0	0	0	0	0	0	0
Pyura stolonifera	0	0	0	0	0	0	0	0
Bryozoa sp1	0	0	0	0	0	0	0	0
Bryozoa sp2	0	0	0	0	0	0	0	0
Bugula flabellata	0	0	1	0	0	0	0	0
*Watersiporia subtorquata**	0	0	0	0	0	0	0	0
Balanus variegates	1	1	1	0	1	1	0	0
*Corophium acherusicum**	0	0	0	0	0	0	0	0
*Elminius modestus**	1	0	0	0	0	0	0	0
Ericthonius sp.	0	0	0	0	0	0	0	0
*Halicarcinus inomminatus**	1	1	1	1	1	1	1	1
Halicarcinus ovatus	0	0	0	0	0	0	0	0
Munida sp.	0	0	0	0	0	0	0	0
Notomithrax minor	0	0	0	0	0	0	0	0
Palaemon dolospina	0	0	0	0	0	0	0	0
Palaemon intermedius	0	0	0	0	0	0	0	0
Parawaldeckia sp.	0	0	0	0	0	0	0	0
*Petrolisthes elongatus**	1	1	1	1	1	1	1	1
Pinnotheres hickmani	0	0	1	0	0	0	1	0
Sphaeromatidae sp1	0	0	0	0	0	0	0	0
Pateriella regularis	0	1	0	0	0	0	0	0
Hirudinea sp.	0	0	0	0	0	0	0	0
Clytia sp.	0	0	0	0	0	0	0	0
Hydroid sp1	0	0	0	0	0	0	0	0
Hydroid sp2	0	0	0	0	0	0	0	0
Aplysia sydneyensis	0	0	0	0	0	0	0	0
*Crassostrea gigas**	1	1	1	1	1	1	1	1
Hiatella australis	0	1	1	0	0	0	0	0
Irus (Irus) cumingii	0	0	0	0	0	0	0	0
Muscula impacta	0	0	0	0	0	0	0	0
*Mytilus galloprovincialius**	1	1	1	0	1	0	1	1
Nudibranch sp1	0	0	0	0	0	0	0	0
Notoplana australis	0	1	1	0	1	1	0	1
Boccardia polybranchia	0	0	0	0	0	0	0	0
Ciriformia sp.	0	0	0	1	0	0	0	0
Dorvelleid sp.	0	0	0	0	0	0	0	0
Harmothoe waahli	1	1	1	1	1	1	1	1
Neanthes cricognatha	0	1	1	0	0	0	0	1
Ophiodromus sp.	0	0	0	0	0	0	0	0
Polynoidae sp1	0	0	0	0	0	0	0	0
Pomatoceros taeniata	0	0	0	0	0	0	0	0
Spirorbid sp.	0	0	0	0	0	0	0	1
Porifera sp1	0	0	0	0	0	0	0	0
Porifera sp2	0	0	0	0	0	0	0	0
Porifera sp3	0	0	0	0	0	0	0	0
Porifera sp4	0	0	0	0	0	0	0	0
Total	8	11	13	6	9	7	8	10

Appendix 1: Species recorded on settlement plates in thermal trial

Table A1: Species recorded from plates examined prior to the experimental trails. Plates T1-1 to T1-3 were collected on 27 May, 2005; plates T2-1 to T2-3 were collected on 25 July, 2005.

	T1-1	T1-2	T1-3	T2-1	T2-2	T2-3
Ascidian sp1	1	0	0	0	1	1
*Botrylloides leachii**	1	0	1	1	1	1
Ciona intestinalis	0	1	1	1	1	1
Cnemidocarpa radicosa	0	0	1	1	0	1
Herdmania momus	0	1	1	1	1	1
Pyura stolonifera	1	1	1	1	1	1
Bryozoa sp1	1	0	0	1	1	0
Bryozoa sp2	0	0	0	0	0	1
Bugula flabellata	1	1	1	0	1	1
*Watersiporia subtorquata**	1	1	1	1	1	0
Balanus variegates	1	1	0	1	1	1
*Corophium acherusicum**	1	0	1	0	0	0
*Elminius modestus**	0	1	1	1	1	1
Ericthonius sp.	1	1	1	0	1	1
*Halicarcinus inomminatus**	1	1	1	1	1	1
Halicarcinus ovatus	1	0	0	0	1	0
Munida sp.	0	0	1	0	0	1
Notomithrax minor	1	1	1	1	1	1
Palaemon dolospina	1	0	0	1	0	0
Palaemon intermedius	0	1	1	1	1	1
Parawaldeckia sp.	1	0	1	0	1	0
*Petrolisthes elongatus**	1	1	1	1	1	1
Pinnotheres hickmani	1	0	1	0	0	1
Sphaeromatidae sp1	1	1	1	1	1	1
Pateriella regularis	1	1	1	1	0	1
Hirudinea sp.	0	0	0	0	0	1
Clytia sp.	0	0	0	0	0	1
Hydroid sp1	1	1	0	1	1	1
Hydroid sp2	0	0	1	1	1	0
Aplysia sydneyensis	0	1	0	0	0	1
*Crassostrea gigas**	1	1	1	1	1	1
Hiatella australis	1	0	0	0	0	1
Irus (Irus) cumingii	0	1	1	1	1	1
Muscula impacta	1	1	0	1	0	0
*Mytilus galloprovincialius**	0	1	1	1	1	1
Nudibranch sp1	0	0	1	1	0	0
Notoplana australis	1	0	0	0	1	1
Boccardia polybranchia	1	1	1	1	1	0
Cirriformia sp.	1	0	0	0	1	1
Dorvelleid sp.	1	0	0	0	0	0
Harmothoe waahli	1	1	1	1	1	1
Neanthes cricognatha	1	1	1	1	0	1
Ophiodromus sp.	0	1	0	0	1	1
Polynoidae sp1	1	1	1	1	1	1
Pomatoceros taeniata	1	1	1	1	1	0
Spirorbid sp.	1	0	0	0	1	1
Porifera sp1	0	1	1	1	0	0
Porifera sp2	1	1	0	1	1	1
Porifera sp3	0	1	1	1	0	0
Porifera sp4	0	0	0	0	0	1
Total	32	29	31	31	32	36

Appendix 2: Donor Port Baseline Survey Results

Baseline survey results showing non-indigenous species identified from donor port regions in Australia and New Zealand

Phylum, Class	Order	Family	Genus and species	Hobart	Fremantle	Bluff	Lyttelton
Bryozoa							
Gymnolaemata	Cheilostomata	Bugulidae	*Bugula flabellata*	X	X	X	X
Gymnolaemata	Cheilostomata	Bugulidae	*Bugula neritina*	X	X		X
Gymnolaemata	Cheilostomata	Candidae	*Tricellaria inopinata*				X
Gymnolaemata	Cheilostomata	Candidae	*Tricellaria occidentalis*	X	X		
Gymnolaemata	Cheilostomata	Cryptosulidae	*Cryptosula pallasiana*		X		X
Gymnolaemata	Cheilostomata	Electridae	*Conopeum seurati*				X
Gymnolaemata	Cheilostomata	Watersiporidae	*Watersipora subtorquata*	X	X	X	X
Gymnolaemata	Cheilostomata	Membraniporidae	*Membranipora membranacea*	X			
Gymnolaemata	Ctenostomata	Vesiculariidae	*Bowerbankia gracilis*	X			
Gymnolaemata	Ctenostomata	Vesiculariidae	*Bowerbankia imbricata*	X			
Cnidaria							
Anthozoa	Actiniaria	Haliplanellidae	*Haliplanella lineata*				X
Hydrozoa	Hydroida	Sertulariidae	*Symplectoscyphus indivisus*			X	
Hydrozoa	Hydroida	Clavidae	*Cordylophora caspia*	X			
Hydrozoa	Hydroida	Tubulariidae	*Ectopleura crocea*	X			
Hydrozoa	Hydroida	Tubulariidae	*Ectopleura dumortieri*	X			
Hydrozoa	Hydroida	Tubulariidae	*Turbellaria ralphi*		X		
Hydrozoa	Hydroida	Bougainvilliidae	*Bougainvillia muscus*	X			
Crustacea							
Malacostraca	Amphipoda	Corophiidae	*Apocorophium acutum*				X
Malacostraca	Amphipoda	Corophiidae	*Monocorophium acherusicum*				X
Malacostraca	Amphipoda	Corophiidae	*Monocorophium sextonae*				X
Malacostraca	Amphipoda	Ischyroceridae	*Jassa slatteryi*				X
Malacostraca	Amphipoda	Stenothoidae	*Stenothoe sp. aff. S. gallensis*				X
Malacostraca	Brachyura	Cancridae	*Cancer gibbosulus*				X
Malacostraca	Brachyura	Cancridae	*Cancer amphioetus*			X	
Malacostraca	Brachyura	Cancridae	*Metacarcinus novaezelandiae*	X		(n)	(n)
Malacostraca	Brachyura	Portunidae	*Carcinus maenas*	X			
Malacostraca	Brachyura	Hymenosomatidae	*Halicarcinus innominatus*	X		(n)	(n)
Malacostraca	Anamura	Porcellanidae	*Petrolisthes elongatus*	X		(n)	(n)
Mollusca							
Bivalvia	Veneroida	Semelidae	*Theora lubrica*	X			X
Bivalvia	Veneroida	Mactirdae	*Raeta pulchella*	X			
Bivalvia	Veneroida	Veneridae	*Venerupis largillierti*				
Bivalvia	Neotaenioglossa	Turritellidae	*Maoricolpus roseus*	X		(n)	(n)
Bivalvia	Myoida	Corbulidae	*Corbula gibba*	X			
Bivalvia	Nuculoida	Neilonellidae	*Neilo australis*	X			
Bivalvia	Ostreoida	Ostreidae	*Crassostrea gigas*	X			
Bivalvia	Mytiloida	Mytilidae	*Mytilus galloprovincialis*	(n)		(n)	(n)
Bivalvia	Mytiloida	Mytilidae	*Musculista senhousia*		X		
Polyplacaphora	Neolocrita	Chitonidae	*Chiton glaucus*	X		(n)	(n)

Appendix 2: Donor Port Baseline Survey Results

Phylum, Class	Order	Family	Genus and species	Hobart	Fremantle	Bluff	Lyttelton
Annelida							
Polychaeta	Canalipalpata	Sabellidae	*Euchone limnicola*	X			
Polychaeta	Canalipalpata	Spionidae	*Boccardia proboscidea*	X			
Polychaeta	Sabellida	Sabellidae	*Sabella sallanzanii*		X		
Phycophyta							
Phaeophyceae	Laminariales	Alariaceae	*Undaria pinnatifida**	X			X
Chlorophycaea	Bryopsidales	Codiaceae	*Codium fragile tomentosoides*	X			
Rhodophyceae	Gigartinales	Phyllophoranceae	*Schottera nicaeensis*	X			
Rhodophyceae	Ceramiales	Ceramiaceae	*Griffithsia crassiuscula*	X		X	X
Rhodophyceae	Ceramiales	Rhodomelaceae	*Polysiphonia brodiaei*	X		X	X
Rhodophyceae	Ceramiales	Rhodomelaceae	*Polysiphonia subtilissima*				X
Echinodermata							
Asteroidea	Forcipulatida	Asteriidae	*Asterias amurensis*	X			
Asteroidea	Forcipulatida	Asteriidae	*Astrostole scabra*	X			
Asteroidea	Spinulosida	Asterinidae	*Patiriella regularis*	X		(n)	(n)
Urochordata							
Ascidiacea	Aplousobranchia	Cionidae	*Ciona intestinalis*	X	X		X
Ascidiacea	Aplousobranchia	Ascidiidae	*Ascidiella aspersa*	X	X		
Ascidiacea	Stolidobranchia	Styelidae	*Cnemidocarpa sp.*	X			X
Ascidiacea	Stolidobranchia	Styelidae	*Botrylloides leachi*	X			
Ascidiacea	Stolidobranchia	Styelidae	*Botryllus schlosseri*	X			
Chordata							
Oestichthyes	Salmoniformes	Salmonidae	*Salmo trutta*	X			
Oestichthyes	Salmoniformes	Salmonidae	*Salmo salar*	X			
Oestichthyes	Salmoniformes	Salmonidae	*Oncorhynchus mykiss*	X			
Oestichthyes	Perciformes	Gobiidae	*Tridentiger trigonocephalus*		X		
Porifera							
Calcarea	Leucosolenida	Heteropiidae	*Grantessa intusarticulata*			X	
Calcarea	Leucosolenida	Leucosoleniidae	*Leucosolenia cf. discoveryi*			X	
Demospongiae	Halichondrida	Dictyonellidae	*Stylotella agminata*			X	
Demospongiae	Halisarcida	Halisarcidae	*Halisarca dujardini*			X	
Demospongiae	Poecilosclerida	Chondropsidae	*Chondropsis topsentii*			X	
Demospongiae	Poecilosclerida	Chondropsidae	*Psammoclema cf. crassum*			X	
Pyrrophycophyta							
Dinophyta	Gymnodiniales	Gymnodiniaceae	*Gymnodinium catenatum*	X			
Dinophyta	Gonyaulacales	Goniodomataceae	*Alexandrium catenella*	X			
Dinophyta	Gonyaulacales	Goniodomataceae	*Alexandrium tamarense*	X	X		

New Zealand port data provided by Biosecurity New Zealand. Hobart data extracted from Aquenal (2002). Fremantle data extracted from Hewitt et al., 2000. X indicates presence as an NIS, (n) indicates the species is present but native to that region.

Appendix 3: Recommendations for Aurora Australis

Specific assessment and recommendations relating to RSV *Aurora Australis*

Description

RSV *Aurora Australis* (*"Aurora"*) is the Antarctic Division's main research and re-supply vessel which has been used every season since 1990. *Aurora* typically spends six to eight months of the year at sea on research and re-supply voyages and four to six months months[19] tied up in the docks in Hobart. The hull is coated with an abrasion resistant epoxy coating which does not contain a biocide. Sheltered areas such as sea chests and bow and stern thruster housings are painted with antifoulant.

Entrainment risks

- Hull fouling from long lay ups in port over winter;
- Colonisation of recessed areas (sea chests, etc) and internal water systems;
- Use and exchange of ballast water;
- Use of research gear e.g. CTD, fishing net, on board water sampling apparatus;
- Use of auxiliary craft e.g. Zodiacs, life boats (used in drills in Hobart docks); and
- Use of anchors

Translocation risks

- Short voyage time from Hobart direct to Macquarie Island;
- Hull not protected with antifoulant; and
- Relatively slow vessel speed resulting in low shear stresses

Discussion

The hull of this vessel represents a major translocation risk, especially after the long lay up in Hobart docks during the winter, when there is significant build-up of fouling on the hull and in the internal water systems and risk of entrainment of potential pest organisms on the hull.

The solution to the problem of a fouled hull to date has, essentially, been to ignore it, in the understanding that the fouling will be scraped off during the first encounter with the pack ice. While this may be a pragmatic solution to hull fouling, it cannot be recommended as best practice. There are risks in translocating marine organisms to Antarctica and the sub-Antarctic islands and a fouled hull will have a detrimental effect on fuel consumption. It is recognized that annual dry docking and application of antifoulant coating would be prohibitively expensive; additionally the pack ice will rapidly erode the antifoulant coating thereby releasing toxic materials into the Antarctic environment.

Two potential solutions are offered but it should be made very clear that these will require detailed investigation and a risk assessment to be carried out before considering implementation. The first is to moor *Aurora* in the fresh water stream of the River Derwent during the winter. It is

[19] Aurora's last voyage in the 2005-06 field season ended on 13 April 2006. The first voyage of the 2006-07 field season starts on 10 October 2006.

not known whether a secure mooring is available in a position where the entire hull is kept in fresh water but this could be investigated. It is important to emphasise that the entire hull must be in fresh water and that the lower part of the hull does not protrude into the saltwater wedge. The second potential solution is to clean *Aurora's* hull *in situ* in Hobart docks before the beginning of each season. There are two issues involved in this. The first is that it would need a diver to do it. In other parts of the world, divers regularly clean vessel hulls *in situ* using cleaning apparatus such as the Brush-Kart system[20]. In Australia this would contravene the ANZECC Code of Practice for Antifouling and In-Water Hull Cleaning and Maintenance (ANZECC 2000). The intent of this code of practice, however, is principally to prevent pollution from antifoulant coatings so this would not apply in this case and the organisms on the hull would most likely be from locally recruited fauna and flora. The Code of Practice states:

(Procedures (2)) "In-water hull cleaning is prohibited, except under extra ordinary circumstances and permission will not normally be granted".

The Code does, however, provide scope for issuing a permit under exceptional circumstances. It is not known, at this stage, which Tasmanian authority might issue such a permit.

Aurora is not fitted with a marine growth protection system (MGPS)[21] to protect the internal water systems (P. Dixon *pers. comm.*). The installation of a MGPS should also be investigated. If an MGPS is fitted, it should be kept separate from the scientific water sampling system as it could contaminate the water.

Management measures

If the current regime of antifoulant application is to be continued, the following management measures are recommended:

- Vessel hull and internal water system cleanliness are critical to reduce entrainment and translocation risks. To achieve this the following investigations are recommended:
    a. The efficacy and practicability of mooring *Aurora* in fresh water during the winter lay up.
    b. In-water hull cleaning by diver immediately prior to the commencement of the summer shipping season.
    c. The installation of a marine growth protection system to protect the internal water system.
- Ballast water must not be released within 200 nautical miles of the island (IMO Guidelines);
- All scientific equipment (e.g. CTD) and operational gear (e.g. Zodiacs and life boats) tested in coastal waters in Tasmania should be thoroughly cleaned with fresh water and inspected for organisms before stowage;
- The water sampling system should not be made operational until the vessel has reached a water depth of greater than 200 metres to avoid ingestion of larvae, etc;
- Ships anchors, if used in Tasmanian coastal waters, should be cleaned of all sediment with a high pressure hose before stowage.

[20] See: http://phosmarine-brush-kart.com/
[21] See, for example: http://cathodic.co.uk/Cuprion%20Brochure.pdf

Appendix 4: Baseline Survey Methodology

Macquarie Island

During the 2002/2003 Austral summer, researchers conducted baseline surveys of Macquarie Island coastal communities. Two sites on the East Coast of the island were selected for base line survey of marine communities: Garden Cove and Sandy Bay (see Figure 2). The selection of these sites was based upon a variety of features that may predispose the sites to a higher risk of establishment by introduced species (see discussion).

Surveys conducted at Macquarie Island were modified from the Hewitt and Martin (1996, 2001) base-line survey protocol which has been adopted by the International Maritime Organisations GloBallast Port Survey Program. Modifications were adopted due to the severe nature of the sub-Antarctic climate, due to the absence of established port facilities, and due to safety constraints that precluded the use of SCUBA equipment.

Five inter-tidal transects were conducted in each bay selected for the survey. Transect lines were separated by 5m and ran perpendicular to the waterline extending from the highest marine organisms down to the mean low water mark. Transects were subdivided into five equal increments and quadrat information and samples were collected at each increment. Each quadrat consisted of a one square meter area in which all organisms observed during a 15minute search effort were collected.

Qualitative collections from the sub-tidal were obtained by breath-hold divers with snorkeling apparatus. Six twenty-minute dives were conducted to a depth of 2m at the Garden Cove site creating a total of 2hrs of search effort. Due to surge conditions and wildlife hazards at Sandy Bay, only three twenty-minute dives could be conducting providing a total search effort of only 1hr.

Auckland Islands

A research trip to the Auckland Islands was conducted from 05-18 February 2004. During this period dives were conducted at seven sites along the eastern coast of the island system and within Carnley Harbour and Port Ross. Survey sites were selected in regions of high historical and modern vessel traffic corresponding to potential sites of anthropogenic impacts, and regions with the highest risk of establishment for non-indigenous organisms. Figure 3 shows the location of dive sites and indicates whether full surveys or qualitative collections were conducted at each site.

A preliminary dive conducted at the Hardwick Settlement site indicated that the highest diversity of organisms in shallow bays was located at a depth of 2-3 metres. At >4m rocky reef communities generally subsided into soft-sediment in-faunal communities dominated by *Munida sp.* (Fa. Galatheidae). Due to time limitations restricting the design to one dive per site, and as the survey was intended to target epi-benthic communities it was decided to concentrate on the three metre depth zone in the sampling strategy.

Appendix 4: Baseline Survey Methodology

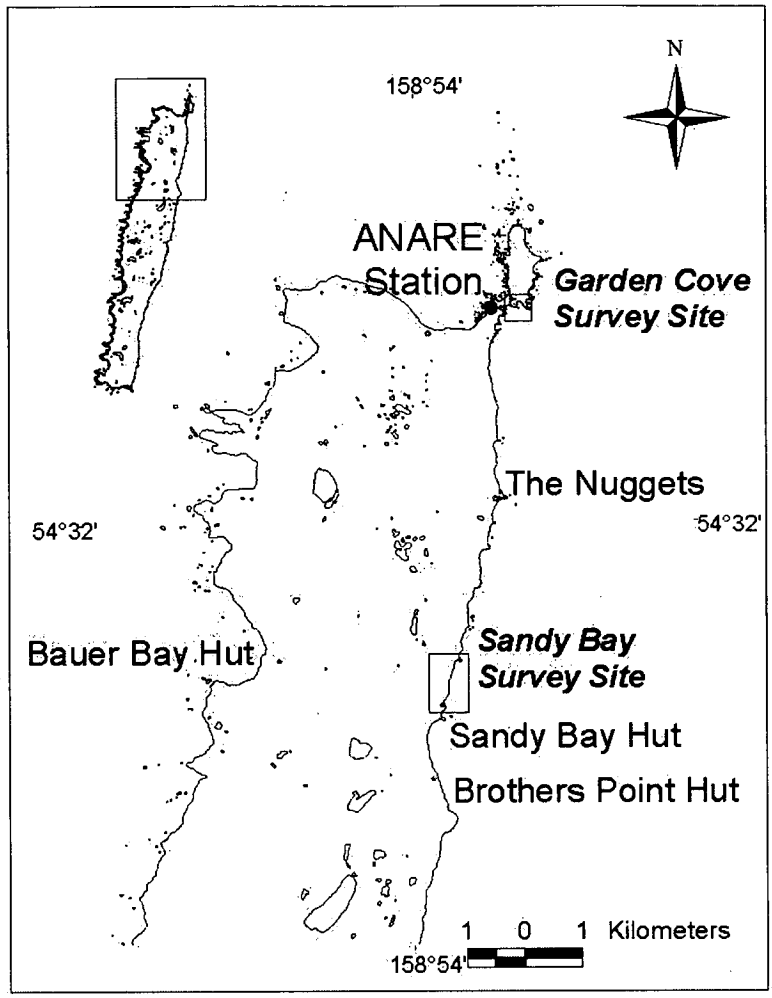

Figure A1: Geographical location of survey sites at Macquarie Island. Surveys were conducted at Garden Cove and Sandy Bay.

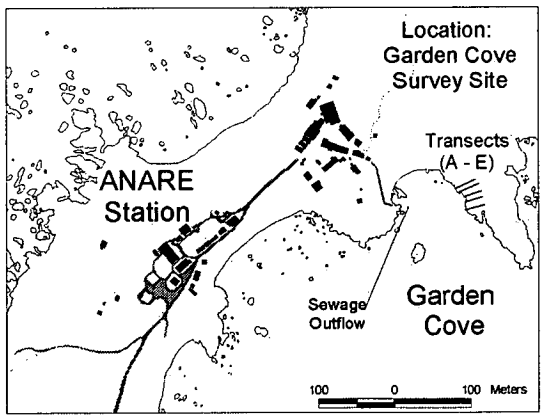

Figure A2: Garden Cove Survey Site. Transects A-E were conducted on the northern shore of the sheltered cove

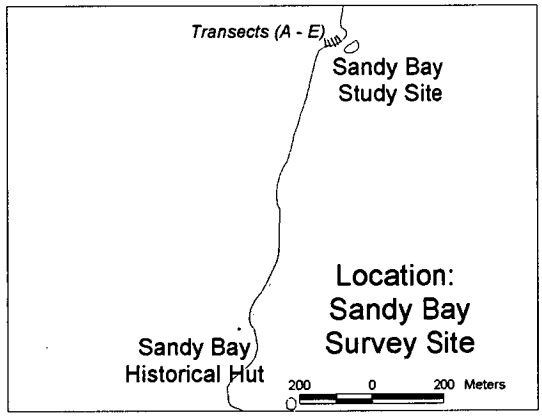

Figure A3: Sandy Bay Survey Site. Transect were conducted on a sheltered, rocky shore to the north of Sandy Bay Beach.

Appendix 4: Baseline Survey Methodology

Collections were obtained according to the following protocol:

- 50m transect laid out at 2m depth parallel to shore line
- 10 x 1m quadrats were deployed at random intervals along transect by 2 divers. A representative collection of all invertebrates within each quadrat was collected and preserved in 10% formalin for identification (sponges and some other taxa were preserveed in 70% EtOH). The samples obtained from the survey are listed in table 1. A total of 85 samples were collected during the study.
- 30 x 0.1m photo quadrats were collected from each transect to provide % cover data and to describe community structure/dominant species etc.
- Qualitative collections of conspicuous organisms not observed in the quantitative design were collected by a diver swimming the length of the 50m transect, and during vertical transects from 0-4m depth.

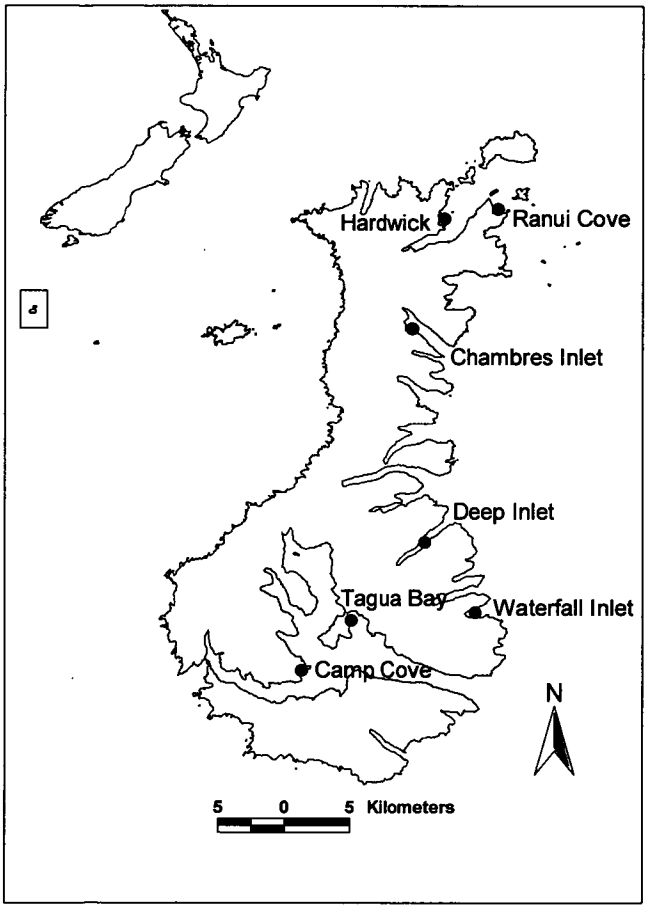

Figure A4: survey sites at the Auckland Islands

Appendix 4: Baseline Survey Methodology

Identification and classification of species

Due to limitations in time and collection size, the survey focused upon invertebrate animals and algal species were not identified. Invertebrates in each group were identified to Family level and voucher specimens were then examined by recognized taxonomic exerts in each major group to gain accurate species-level identification (see Table A2).

Taxa	Specialist
Bryozoa	Dennis Gordon, NIWA
Hydrozoa	Jan Watson, Museum Victoria
Echinodermata	Tim O'Harra, Museum Victoria
Polychaeta	Robin Wilson, Museum Victoria
Crustacea	Genefor Walker-Smith, Tasmanian Museum and Art Gallery
Pycnoginidae	David Staples, Museum Victoria
Ascidiacea	Patricia Mather, Queensland Museum (consultation only)
Porifera	John Hooper, Queensland Museum (consultation only)

Appendix 5: Species recorded from the Auckland Islands

Taxa	Species	Ranui Cove	Waterfall Inlet	Tagua Bay	Hardwick	Camp Cove	Chambres Inlet	Deep Inlet	First recording
Cnidaria	*Orthopyxis crenata*	x	x		x				
	Helecium corrugatissimum	x	x		x				
	Amphisbetia minima				x				
	Eudendrium deforme				x				
	Salacea ?desmoides				x				
	Sertularella robusta				x				
	Plumularia opima		x		x				
	Orthopyxis mollis		x		x				
	Symplectoscyphus sp.	x			x				
	Hydractinia ?parvispina		x						
	Unidentified sp.			x					
	Anemone spA	x	x		x			x	
	Anemone spB		x		x			x	
Bryozoa	*Diaperoecia purpurascens*				x		x		Y
	Idmidronea sp.						x		Y
	Tubulipora sp.	x	x		x	x	x	x	Y
	Disporella sp.		x						Y
	Alderina pacifera	x							Y
	Chaperia granulosa	x	x	x	x			x	
	Chaperiopsis cervicornis		x		x				Y
	Beania elongate						x		Y
	Beania magellanica	x	x		x				Y
	Emma rotunda	x			x				Y
	Tricellaria aculeate	x	x		x				Y
	Ophaeophora lepida	x	x		x				
	Celleporella bathamae	x	x	x	x				Y
	Celleporella buskiana		x		x				Y
	Celleporella delta	x	x		x				
	Celleporella n.sp.	x							Y
	Escharoides n.sp.			x	x		x		
	Exochella armata	x	x	x	x	x			Y
	Exochella sp.	x	x		x				Y
	Parkermavella microrhyncha		x		x				
	Schizosmittina conjuncta.		x		x				
	Schizosmittina n.sp.		x		x				Y

Appendix 5: Species recorded from the Auckland Islands

Taxa	Species	Ranui Cove	Waterfall Inlet	Tagua Bay	Hardwick	Camp Cove	Chambres Inlet	Deep Inlet	First recording
	Hippadenella clivosa				x				
	Cosciniopsis vallata	x		x	x				Y
	Lacerna styphelia		x		x				Y
	Fenestrulina incompta		x		x		x		Y
	Fenestrulina thyreophora				x				
	Chiastosella watersi	x	x		x		x		Y
	Osthimosia sp.	x							Y
Platyhelminthes	*Notoplana sp*			x	x				
Mollusca	*Aulacomya atra maoriana*	x	x	x	x				
	Cyamiomactra problematicum	x		x	x				
	Gaimardia forsteriana aucklandica				x				
	Kiddaria costata				x				
	Lissarca aucklandica	x	x	x	x	x	x		
	Mysella unidentata				x				
	Mytilus galloprovincialis			x	x			x	
	Ruditapes largillierti				x				
	Tawera rosa			x					
	Actinoleuca campbelli campbelli	x		x	x		x		
	Antiguraleus sp.				x				
	Baccinulum pertinax pertinax				x				
	Benhaminia obliquata			x					
	Cantharidus capillaceous	x	x		x	x			
	Cellona strigilis strigilis				x				
	Chemnitzia sp.			x	x				
	Eatoniella fuscosubucula			x	x				
	Eatoniella kerguelensis chiltoni			x	x				
	Eatoniella poutama				x				
	Eatoniella roseola			x	x	x	x		
	Eatoniella smithi				x				
	Eatoniella verecunda			x	x				
	Epsithais lucunosus		x						
	Haliotis virginea huttoni				x				
	Margarella antipodium rosea				x				
	Marginella stewartiana			x					
	Onobia delicatula				x				
	Onobia fallai				x				
	Paxula subantarctica sorenseni		x		x				

Appendix 5: Species recorded from the Auckland Islands

Taxa	Species	Ranui Cove	Waterfall Inlet	Tagua Bay	Hardwick	Camp Cove	Chambres Inlet	Deep Inlet	First recording
	Paxula subantarctica subantarctica			x	x	x	x		
	Sigapatella novaezelandiae		x		x				
	Thoristella chathamensis		x	x	x	x			
	Tubbreva exultata exultata			x	x		x		
	Xenostrobus pulex			x					
	Xymene sp.				x				
	Isochiton circumvallatus			x	x				
	Plaxiphora aurata	x			x				
	Rhyssoplax aerea	x		x	x				
	Rhyssoplax sp1				x				
	Sypharochiton pelliserpentis	x		x	x				
	Callochiton mortenseni				x				
	Callochiton empleurus				x				
	Acanthochiton zealandica			x	x				
	Pleurobranchidae sp1				x				
Polychaeta‡	Capitellidae spA	x							
	Cirratulidae spA	x		x	x				
	Glyceridae spA			x					
	Hesionidae spA				x				
	Hesionidae spB				x	x			
	Hesionidae spC			x	x				
	Lumbrenereidae spA			x	x				
	Lumbrenereidae spB				x				
	Neanthes cricognatha	x	x	x	x		x		
	Nereis spA	x		x	x				
	Nereis spB	x							
	Platynereis spA				x				
	Platynereis spB				x				
	Platynereis spC	x							
	Platynereis spD	x							
	Platynereis spE			x	x				
	Armandia spA				x				
	Eumida spA			x					

Appendix 5: Species recorded from the Auckland Islands

Taxa	Species	Ranui Cove	Waterfall Inlet	Tagua Bay	Hardwick	Camp Cove	Chambres Inlet	Deep Inlet	First recording
	Sabellidae spA					x			
	Polydora Group spA			x					
	Polydora Group spB			x	x				
	Polydora Group spC		x	x	x				
	Spionidae spA			x					
	Pomatoceros taeniata	x		x	x	x	x		Y
	Spirorbidae spA	x	x	x	x	x	x	x	
	Syllidae spA			x					
	Syllidae spB	x		x					
	Syllidae spC			x	x				
	Syllidae spD			x					
	Terebellidae spA	x		x	x				
Sipuncula	Sipuncula spA			x	x				
Pycnogonidae	*Achelia spA*			x					
	Achelia spB	x							
	Achelia spC		x						
	Achelia spD	x	x	x					
	Achelia spE			x					
	Ammothea spA			x					
	Ammothea spB			x	x				
	Unidentified sp			x					
	Pallenopsis spA			x					
	Pallenopsis spB			x					
	Austrodecus spB			x					
Crustacea*	*Balanus campbelli*	x	x		x				
	Balanus decorus	x	x		x				
	Epopella plicata	x							
	Metacarcinus novaezelanidae			x		x			
	Nectocarcinus bennetti					x			
	Halicarcinus planatus	x		x	x				
	Porcellanopagrus edwardsii		x		x				
	Lophopagrus lacertosus	x	x		x				
	Batadotea elongate				x				
	Paridotea ungulate				x		x		
	Plakarthrium typicum				x				
	Aaroidae sp1	x	x		x				
	Aaoridae sp2				x				
	Aaoridae sp3	x	x		x				

Appendix 5: Species recorded from the Auckland Islands

Taxa	*Species*	Ranui Cove	Waterfall Inlet	Tagua Bay	Hardwick	Camp Cove	Chambres Inlet	Deep Inlet	First recording
	Aoriodae sp4		x		x				
	Dexaminidae sp1						x		
	Dexaminidae sp2		x		x	x			
	Dexaminidae sp3		x		x				
	Dexaminidae sp4				x				
	Caprellidae sp1	x			x				
	Caprellidae sp2		x	x	x				
	Leucothoidae sp1				x				
	Eusiridae sp1				x				
	Eusiridae sp2		x						
	Melitidae sp1	x	x						
	Lysanassidae sp1				x				
	Lysianassidae sp2				x				
	Talitridae sp1	x							
	Tanaidae sp1				x				
	Tanaidae sp2	x	x	x	x	x			
Echinodermata	*Trochodota dunedenensis*			x					
	Squamocnus brevidentis			x					
	Henricia lukinsi						x		
	Henricia aucklandiae			x			x		
	Paranephanthia aucklandensis			x					
	Anasterias laevigata			x					
	Amphiura amokurae				x				
	Ophiomyxa brevirima			x					
	Ophiopeza cylindrical			x					
	Amphipholis squamata	x		x	x				
	Amphiura magellanica			x					
Ascidiacea	*Asterocarpa cerea*				x				
	Botrylloides leachii			x	x				
	Corella eumyota	x							
TOTALS	173	53	50	71	120	15	19	6	

Appendix 6: Species recorded from Macquarie Island

Taxa	Species	Garden Cove						Sandy Bay					
		1	2	3	4	5	Subtidal	1	2	3	4	5	Subtidal
Bryozoa	*Beania sp.1*						x						
	Chaperia sp1					x							
	Hippadenella sp.1					x	x				x	x	
	Hippadenella sp.1												
	Notoplites sp1						x						
	Tricellaria cf. aculeate										x	x	x
Chordata	*Harpagifer georgianus*				x		x						x
	Hemichordata sp1				x	x						x	
	Paranotothenia magellanica					x	x						
	Zanclorhynchus spinifer					x	x				x		x
Cnidaria	Anemone sp1				x	x	x			x	x	x	x
	Anemone sp2												x
	Anemone sp3					x							
	Anemone sp4					x						x	
	Anemone sp5					x	x					x	
	Stauromedusae sp1										x		
	Tubularia sp.1												x
Crustacea	Apseudidae sp1												x
	c.f. Acontiostoma marionis						x						x
	c.f. Munna instructa										x	x	
	Cassinadonopsis emerginata					x	x						
	Eusiridae sp. 1				x	x					x	x	x
	Eusiridae sp. 2		x		x								
	Eusiridae sp. 3					x				x			
	Expheromorpha gigas	x	x	x	x	x	x	x			x	x	x
	Halicarcinus planatus					x	x				x	x	x
	Hyale hirtipalma		x	x	x	x		x		x	x	x	x
	Hyallidae sp1					x							
	Hyallidae sp2										x		
	Iais pubescens			x	x	x	x	x		x	x	x	
	Jassa justi							x			x	x	x
	Joeropsis curvicornis					x	x						
	Kerguelenia antiborealis							x					x
	Limnoria stephenseni											x	
	Paramorea sp.1	x		x	x	x	x	x		x	x	x	x
	Parawaldeckia kiddri			x		x		x		x		x	
	Tanaidaceae sp. 1			x	x			x		x	x		
	Tanaidaceae sp. 2		x	x				x		x			
Echinodermata	*Anasterias directa*				x	x	x				x	x	x
	Anasterias mawsonni					x	x					x	x
	Cycethra frigida						x					x	x
	Pseudechinus novaezealandiae					x	x						
	Pseudocnus laevigatus					x	x						
	Pseudopsolus macquariensis					x	x			x		x	x
	Trachythyone macphersonae					x	x					x	x
Terrestrial	Insect sp1	x	x					x					
	Insect sp2	x	x					x					
	Insect sp3	x											

Appendix 6: Species recorded from Macquarie Island

Taxa	Species	Garden Cove						Sandy Bay					
		1	2	3	4	5	Subtidal	1	2	3	4	5	Subtidal
	Insect sp5							x					
	Acarina sp1				x								
Mollusca	*Cantharidus coruscans*					x	x				x	x	x
	Falsilunatia pisum				x	x	x						x
	Gaimardia trapesina												x
	Hemiathrum setulosum					x	x					x	x
	Kerguelenella innominata			x						x	x		
	Kerguelenella lateralis			x	x	x		x		x	x	x	
	Kidderia bicolor		x	x	x	x		x		x	x	x	x
	Kidderia oblonga			x	x	x						x	x
	Laevilitorina caliginosa	x	x	x	x	x		x		x	x	x	x
	Laevilitorina hamiltoni			x								x	
	Lasae rubra rossiana	x	x	x	x	x	x	x		x	x		x
	Margenella sp. 1						x						x
	Margenella sp. 2					x							
	Nacella macquariensis			x	x	x	x			x	x	x	x
	Plaxiphora auratus					x	x				x	x	x
Nematoda	Nematode sp1											x	
Nemertea	Nemertean sp1				x							x	
Oligochaeta	Oligochaeta sp1	x	x					x		x	x		
	Oligochaeta sp2	x	x					x		x	x	x	
Platyhelmenthes	Platyhelmenthes sp1			x	x					x	x	x	
	Platyhelmenthes sp2			x									
	Platyhelmenthes sp3			x	x			x			x		
	Platyhelmenthes sp4											x	
Polychaeta	*Abarenicola assimilis insularum*					x							
	Axiothella quadrimaculata										x		
	Boccardia cf. polybranchia						x					x	
	Cirratulidae sp1											x	x
	Cirratulidae sp2											x	
	Cirratulidae sp3						x						
	Cirratulus sp1										x		x
	Cirratulus sp2											x	x
	Eulalia sp1						x				x	x	x
	Exogone sp1												x
	EXOGONINAE sp1						x				x	x	x
	Lumbrenidae sp1						x						x
	Lumbrenidae sp2						x						
	Lumbrenidae sp3						x						
	Margenella macquariensis					x							x
	Neanthus kerguelensis					x	x					x	x
	Neolepra cf streptochaetae						x						
	Nereididae sp1										x		
	Neries sp1				x								x
	Neries sp2												x
	Polychaete sp1	x	x	x	x						x		
	Polychaete sp2				x						x		
	Polychaete sp2				x	x							x

Appendix 6: Species recorded from Macquarie Island

Taxa	Species		Garden Cove						Sandy Bay					
			1	2	3	4	5	Subtidal	1	2	3	4	5	Subtidal
	Polychaete sp8							x				x		
	Sabbelidae sp1							x					x	x
	Sabbelidae sp2							x				x	x	x
	Sabbelidae sp3											x	x	x
	Spionidae sp1					x		x			x	x	x	x
	Spiorbidae sp1						x				x	x	x	x
	Spirorbidae sp2											x	x	
	Syllidae sp1												x	
	Syllidae sp2												x	
	Syllinae sp1							x				x	x	x
	Syllinae sp2													
	Terrebellidae sp1							x				x	x	
	Terrebellidae sp2											x		x
	Thelpus plagiostoma						x						x	
	Timarete sp1											x	x	
Pycnogonida	*Endeis australis*							x						
	Austrodecus sp1							x				x		
	Endeis sp1							x						
	Pycnogonium platyophum													x
	Pycnogonum sp 1							x						
	Tanystylum sp2							x					x	
	Tanystylum sp3											x		x
	Tanystylum sp4							x						x
	Tanystylum sp1						x	x						x
TOTALS		122	10	13	19	27	45	52	0	19	20	47	55	54